Research Branch
Technical Bulletin 1997-1E

Soil Landscape Models:

Automated landscape characterization and generation of soil-landscape models

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SOIL LANDSCAPE MODELS:

Automated landscape characterization and generation of soil-landscape models

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This work was conducted with the support of the
Canada-Alberta Environmentally Sustainable Agriculture Agreement (CAESA)

Research Branch
Agriculture and Agri-Food Canada

This document may be cited as:

MacMillan, R. A. and W. W. Pettapiece. 1997. Soil Landscape Models: Automated landform characterization and generation of soil-landscape models. Technical Bulletin No. 1997-1E, Research Branch, Agriculture and Agri-Food Canada, Lethbridge, AB. 75 pp.

Copies of the publication are available from:

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Cat. No A54-8/1997-1E
ISBN 0-662-25634-4

ABSTRACT

Current digital data bases include insufficient information to describe the morphology of landscapes or to link soil types to their most likely positions in the landscape. This bulletin describes the development of a suite of programs to address these deficiencies. Four sets of programs have been developed and applied to a test data set. The first computes and describes the principal morphological attributes of landscapes. The second automatically segments any given landscape into four simple landscape facets defined by relative landscape position and slope gradient. The third automatically assigns soils to the most appropriate landscape facet for any combination of soils and landscape. The fourth constructs simple 3D diagrams to illustrate distribution and relative landscape position of soils for any listed combination of soils and landscape. Application of the programs to new and existing digital soils data sets has the potential to dramatically improve their information content and utility.

EXECUTIVE SUMMARY

Most current soil survey maps and digital data bases provide very limited information about the range of morphometric characteristics of landscapes associated with each soil map unit. Indeed, the minimum data set represented by the National Soils Data Base (NSDB) allows for recording of only one landscape attribute, namely slope gradient expressed as a class. The quality and availability of information describing the location of the main soils in different landform positions within a landscape also varies considerably. If available at all, it must usually be extracted from written descriptions of generalized conceptual soil map units presented in accompanying printed reports. Current digital data bases do not include sufficient information to describe the morphology of the mapped landscapes comprehensively or to link the main named soils to the relative landform positions they are most likely to occupy. These limitations severely restrict the utility of soil databases, particularly with regard to extracting quantitative information for running interpretive programs or simulation models.

The present project is aimed at addressing and rectifying many of these deficiencies in existing soil survey digital data bases. It has four main objectives, namely:

1. To develop, apply and evaluate a suite of programs to automatically compute and describe the principal morphological attributes of landscapes (a landform description program).

2. To develop, apply and evaluate programs to automatically segment any given landform into a limited number of components or facets (i.e. crest, shoulder, mid-slope, toe-slope, depression)

3. To develop, apply and evaluate a program to automatically assign soils listed in a digital data base or soil map unit legend to the most appropriate landform position(s) for any soil-landscape combination.

4. To develop, apply and evaluate a program to automatically generate 2D or 3D images to illustrate schematically the shape and scale of landscapes, the distribution of landform facets and the allocation of soils to individual facets for a given combination of soils and landform.

The present approach assumes a limited number of repeating landform types that experienced mappers can recognize consistently and classify accurately using standard techniques of air photo interpretation. Furthermore, it assumes that detailed digital elevation data (a DEM) from one or more representative sites can be used to establish the principal morphological attributes for a particular type of landform.

Landform description programs based on DEM data are used to describe the morphological attributes for every 5 m by 5 m grid cell of a DEM for an example area. Terrain derivatives computed include slope gradient and aspect as measures of terrain orientation, down-slope and across-slope curvature as measures of terrain shape and

relative relief as a measure of terrain scale. The derivatives up-slope length, down-slope length and relative slope position are used as measures of both landscape scale and landscape context. Finally, the number and size of local watersheds is computed as is the percent of the landscape that contributes to off-site drainage. These measures of drainage pattern are used to differentiate simple landscapes with integrated drainage patterns from complex landscapes with non-integrated drainage.

Several of the above derivatives are used to segment a landform into its components or facets. Four models are evaluated. The first is the seven unit model of Pennock et al., (1987). The second is a simple 4 unit model that uses only relative slope position to allocate each grid cell to one of 4 possible landform facets (Crest, Upper Slope, Lower Slope, Depression). A more detailed 8 unit model considers slope gradient, in addition to relative slope position, to assign each cell to one of 8 possible terrain facets (Level Interfluve, Sloping Shoulder or Crest, Level Upper Slope, Steep Upper Slope, Steep Lower Slope, Level Lower Slope, Sloping Depression Rim and Level Depression). A 4 unit simplification of the 8 unit model was selected for initial use and testing.

Allocation of soils to each of the 4 landform facets is accomplished using an expert system based on possibility analysis (a variant of fuzzy logic) applied to readily available data for each soil. The relative likelihood that a given soil characteristic will occur in a particular landform facet is assessed for each of 6 soil characteristics (i.e. drainage class, salinity class, Sub-Group classification) and then averaged to compute an overall relative likelihood. If **n** soils are listed as occurring in a given polygon, the program considers the relative likelihood of each soil occurring in each landform position to assign soils to facets. Each facet is considered in order in the sequence crest-depression-upper slope-lower-slope. At each stage, the soil considered most likely to inhabit a facet is assigned to that facet until the areal extent of the facet is matched by the areal extent of the soils assigned to it. The next facet in the sequence is then considered and the most likely soils allocated to it and so on, until all facets have been considered and all soils allocated.

This approach captures and makes use of the tacit knowledge accumulated by experienced soils personnel. It is expected that different rule bases will be required for different ecological regions. The process of capturing local expertise to create regional rule bases requires local experts to explicitly codify their tacit knowledge.

The final product of the current project is an automated procedure which produces 3D illustrations of the pattern of distribution of soils for a given combination of soils and landform. Label points are attached to each landscape facet and commercial data base management software is used to automatically link the soil codes and percent extents computed for each landscape facet to the label points in the 3D diagram.

The procedure can be used to create an archive of soil-landform model illustrations to assist users with interpretation and application of the soils data stored in existing and emerging digital soils data bases.

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ACKNOWLEDGMENTS

Much of the computer processing of digital elevation data for the present project was accomplished using public domain programs for processing and displaying raster digital data. In particular, the authors wish to acknowledge use of the Terra Firma software package provided by Dr. J. R. Eyton of South West Texas State University and the PC-Raster package (van Deursen and Wesseling, 1992), especially the Watersh module as provided by Prof. Dr. P. A. Burrough of the University of Utrecht, the Netherlands. Credit for introducing the senior author to the basic principals of morphometric analysis of landforms is also due to Dr. Eyton.

All terrain derivatives were computed using customized programs that re-implemented the logic contained in the above cited software within a database management system (DBMS) environment, specifically ***FoxPro for Windows™***. Any errors in the results produced by the programs are therefore the responsibility of the authors.

The digital elevation model (DEM) for the example site was extracted from data used in Ph.D. research conducted by the senior author. These data were originally collected by Dr. Mark Trudell as part of a research project funded by the Alberta Research Council.

The constructive editorial comments provided by Dr. D. Pennock, of the University of Saskatchewan and Dr. L. Fuller of the University of Manitoba were greatly appreciated.

Funding for this study was provided by the Canada-Alberta Environmentally Sustainable Agriculture (CAESA) agreement.

1. INTRODUCTION

1.1 Background and context

Most current soil survey maps and digital data bases provide very limited information about the range of morphometric characteristics of the landscapes associated with each soil map unit. Indeed, the minimum data set represented by the National Soils Data Base (NSDB) allows for recording of only one landform attribute, namely slope gradient expressed as a class. The quality and availability of information describing the location of the main soils in different landform positions within a landscape also varies considerably. If available at all, it must usually be extracted from written descriptions of generalized conceptual soil map units presented in accompanying printed reports.

The structure of most digital environmental data bases involves the use of key fields containing codes that act as pointers to data tables containing additional detailed information about the entity identified by each code. In both the CAESA-SIP[1] and NSDB[2] digital soils data bases, soil codes are used to identify anywhere from one to five soils for any given polygon (Figure 1). These codes link to expanded descriptions of the attributes of the characteristics of a soil and its horizons in the associated NSDB soil names (SNF) and soil layer (SLF) files (MacDonald and Valentine, 1992).

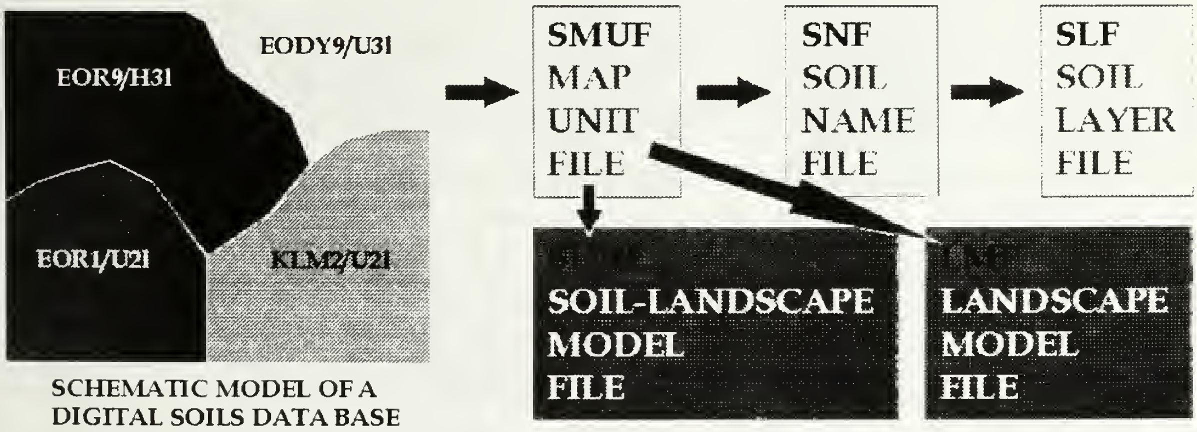


Figure 1. Schematic illustration of a digital soils data base

The CAESA-SIP data base also contains a code for dominant landform type which may be considered analogous to the soil name code. At present, however, there is no equivalent of the SNF or SLF containing detailed information about the attributes of the identified landforms. Landforms have so far only been described in the most general qualitative terms in the procedures manual (CAESA-SIP, 1995).

[1] Canada Alberta Environmentally Sustainable Agriculture Agreement, Soil Inventory Project (CAESA-SIP)
[2] National Soils Data Base (NSDB)

It is interesting to note that while field mapping of soils information is almost always done with reference to landforms and landform characteristics, this relationship is often lost as the soils information becomes delinked from landscapes in the digital data bases used to record the data. In both the CAESA-SIP and NSDB digital databases, there has been no attempt to link named soils to landform position. One is presented with a list of named soils (up to 3 for NSDB and up to 5 for CAESA-SIP) which is believed to best describe the suite of soils characteristic of each mapped polygon. The NSDB database contains no description of landform attributes other than slope gradient and is therefore unable to identify the landform position of listed soils. Also, there is no indication whether the reported slope classes represent the greatest extent of the landscape or are an interpreted "limiting" slope.

The digital data in current (NSDB) and new (CAESA-SIP) digital soils databases is increasingly being used as input to qualitative models (EPIC, Sharpley and Williams, 1990; and WEPP, Flanagan et al., 1994) and interpretive algorithms (LSRS, Agronomic Interpretations Working Group (AIWG), 1995). Many of these models and algorithms require precise numerical data for landform attributes such as slope gradient, slope length and aspect. Such quantitative data is mostly unavailable or must be estimated from the available qualitative descriptions. In addition, quantitative models and algorithms are most frequently applied at the scale of single detailed sites. At these scales, the information contained in the basic digital soils databases is much more useful if the listed soils can be placed in specific positions in the landscape. This capability, which is not currently available, would enable users to partition the landscape into smaller components for modelling and to assign specific soils with specific (and more restricted properties) to each landform component.

Current and emerging digital data bases, therefore, do not include sufficient information to comprehensively describe the morphology of mapped landscapes or to link the main soil types to the relative landform positions they are most likely to occupy. These limitations severely restrict the utility of existing soil databases, particularly with regard to extracting quantitative information for running interpretive programs or simulation models. The present project is aimed at addressing these deficiencies.

1.2 Objective

The overall objective of the present project is:

> *to enhance the information content and utility of digital soils data bases by developing programs to describe the morphology of mapped landforms, to link soil information to landform position and to illustrate expected relationships between soils and landform.*

The project has four main sub-objectives; namely to develop, apply, illustrate and evaluate a suite of programs to automatically:

1. compute and describe the principal morphological attributes of landscapes (a landform morphology description program).
2. segment any given landscape into a limited number of landform components or facets (i.e. crest, shoulder, mid-slope, toe-slope, depression)
3. assign soils listed in a digital data base or soil map unit legend to the most appropriate landform position(s) for any given combination of listed soils and identified landform.
4. generate 3D images to illustrate schematically the shape and scale of landscapes, the distribution of landform facets and the allocation of soils to individual landform facets for a given combination of soils and landform type.

1.3 Relevant literature

1.3.1 Quantitative morphometric description of landforms

Quantitative description of measurable landform attributes is a viable, and potentially more useful, alternative to present qualitative methods. Quantitative description of landform characteristics has a long and impressive history beginning with Strahler (1956) and continuing through Ruhe (1960), Speight (1968) Dalrymple et al. (1968), Young and Evans (1978) and Evans (1972, 1980). Initial efforts (Strahler, 1956; Speight, 1968; Dalrymple et al., 1968) developed and demonstrated the basic concepts of statistical analysis of surface morphology using data obtained by manual measurements obtained from topographical maps.

Computer programs for calculating several of the most common measures of land surface morphology from digital elevation models have been in existence for some time (Wood, 1990a,b; Eyton, 1991; Zevenbergen and Thorne, 1987; Franklin, 1987; Pennock, Zebarth and de Jong, 1987). Most existing programs involve determining spatial derivatives from a gridded DEM by computing first and second derivatives. The simplest approach involves using a numerical approximation procedure based on finite differences to calculate slope gradient and aspect for a 3 by 3 window of a DEM (Tobler, in Davis, 1969; Eyton, 1991). An alternative approach is to fit all, or a portion, of a DEM with a mathematical function such as an exact fitting multi-quadric equation (Hardy, 1971; Eyton, 1974) or a least squares polynomial (Evans, 1980, Young, 1978, Zevenbergen and Thorne, 1987; Pennock et al., 1987) and to use the analytical form of the calculus to obtain the derivatives. Sets of similar programs exist for use with triangular irregular network (TIN) (Weibel and Heller, 1990; Palacios-Velez and Cuevas-Renaud, 1986; Chen, 1988; Heil, 1980) and contour based (Moore at al., 1988; Hutchinson, 1989) representations of terrain.

Quantitative morphometric analysis of landscapes has typically been undertaken for three main reasons (Franklin, 1987). The first (Franklin, 1987; Lanyon and Hall, 1983a,b; Mulla, 1986) is simply to characterize the frequency distribution of measured geomorphological variables within defined bounded units (e.g. landscape units or geological zones). The second is to facilitate analysis and comparison of two or more areas or landscapes believed to have dissimilar morphology arising from differing processes (Strahler, 1956; Band, 1989a,b; Weibel and DeLotto, 1988; Neiman et al., 1987, Mulla, 1986). The third is to facilitate automatic classification of landscapes (Weibel and DeLotto, 1988; Franklin, 1987; Pike, 1988a,b) or automatic segmentation of landscapes into landform elements (Pennock et al., 1987, 1994; Band, 1989a,b; Zebarth and DeJong, 1989a; Fels and Matson, 1996; Blaszczynski, 1997).

Quantitative morphometric analysis of landforms is therefore not new (c.f. Strahler, 1956) but it has become faster, more feasible and more common with the increased availability of high resolution digital elevation models (DEMs) and computer programs for processing and displaying the DEM data. These two factors have lead to a recent renewal in interest in utilizing DEM data to characterize the morphology of landscapes quantitatively and comprehensively (Blaszczynski, 1997; Cialella at al., 1997; Pennock et al., 1987, 1994; Gessler et al., 1996; Fels and Matson, 1996)

1.3.2 Automated segmentation of landforms into landform facets

Segmentation of DEMs for type landscapes into a limited number of landform components, or land facets, is an important aspect of any attempt to automate the production and illustration of soil-landscape models. Existing soil-landscape models are based on the accumulated field experience of soil surveyors that is frequently retained as undocumented tacit knowledge (Indorante et al., 1996; Hudson, 1992; Fels and Matson, 1996). Most experienced surveyors develop a general set of rules relating the distribution of soils to a limited number of conceptual landform positions (i.e. crest, mid-slope, toe-slope). This knowledge is inexact, but has proven to be useful.

Digital elevation data has been used to segment landforms into land facets in several different ways. Pixel based, or point by point, classification methods assume that each pixel's classification depends only on its attribute characteristics, and not on its location in the picture or on the interpretation of neighboring elements (Weibel and De Lotto, 1988; Roger et al., 1996). This lack of spatial context can give rise to classifications that are highly fragmented and spatially non-homogeneous. The widely cited seven unit classification of Pennock et al. (1987) provides an example of a spatially non-homogeneous pixel based classification of landform elements. The basic assumption underlying the pixel based method of Pennock et al. (1987) is that local surface shape is a direct reflection of landform position and that landform position can be inferred from surface shape (curvature and slope gradient). Pennock et al., recognized and offered solutions for the problems of fragmentation that arose from the lack of an explicit measure of landform context in their original classification.

Spatial heterogeneity in pixel based methods can be reduced by filtering the initial classification to remove isolated pixels, but the effect is mainly cosmetic (Weibel and De Lotto, 1988). Additional improvements can be achieved by passing windows of various dimensions over the data set to compute variable scale information for each cell of measures such as grain (longest significant wavelength), texture (shortest wavelength), local relief (maximum elevation difference within the window) and roughness factor (Weibel and De Lotto, 1988; Fels and Matson, 1996; Blaszczynski, 1997).

More spatially homogeneous classifications can be achieved by incorporating context into the classification of individual pixels (Roger et al., 1996). A process called "region growing" can be used to classify individual elements into more homogeneous regions according to their spatial context (Tomita et al., 1979; Starr and Mackworth, 1978). Classes are identified as regions and unambiguously classified pixels are allowed to sequentially influence the interpretation of ambiguous pixels (Weibel and De Lotto, 1988; Pennock et al., 1994). A related process of spatial aggregation uses hydrological connectivity to group pixels and identify regions (Band 1989ab; Gessler et al., 1996).

One important measure of spatial context for landscapes is relative landscape position (i.e. up slope, mid-slope, down slope). Skidmore (1990) described a method for computing relative terrain position in terms of the ratio of the Euclidean distance from a pixel to the nearest valley relative to the total Euclidean distance between the nearest valley and the nearest ridge. Twery et al. (1991) described an equivalent computation for elevation data represented as a triangular irregular network (TIN). Blaszczynski (1997) computed a measure of mean curvature within a variable sized window to establish landscape context. Absolute and relative relief have also been computed by computing the degree (size) and frequency (scale) of change in elevation in a landscape relative to a local base elevation (Franklin, 1987; Meijerink, 1988), by computing the mean elevation difference within a window of varying size (Felds and Matson, 1966) and by removing the regional trend from elevation data and using detrended elevation as a measure of height above local base level (Cialella et al., 1997). Direct determination of terrain position avoids the problem of having to infer terrain position from local shape and provides an ideal measure of landscape context for defining more homogeneous landform regions.

Digital elevation models (DEMs) and indices derived from DEMs (slope, aspect, curvature, drainage area) have been used to assist in both defining and characterizing landscapes in support of soil (Klingbeil et al., 1987; Gressler et al., 1996; Blaszczynski, 1997) and environmental (Skidmore et al., 1991; Lowell, 1990; Frank, 1988; Twery et al., 1991) mapping.

One of the recurring problems in automated extraction of landform attributes from DEMs has been the issue of multiple scales and scale dependency, especially when classifications are based on attributes computed for individual pixels (Weibel and DeLotto, 1988). This is especially true of computations based on analysis of raster

DEMs of a fixed grid size. Several authors have stressed the importance of ensuring that the grid spacing of a raster DEM is of an appropriate size for capturing the scale of variation in the terrain of interest (Strahler, 1956; Weibel and De Lotto, 1988; Band, 1989b, Twery et al., 1991, Wilson, 1997; Felds and Matson, 1996; Zhang and Montgomery, 1994; Quinn et al., 1995).

Hierarchical classifications (Catanzariti and Mackworth, 1978; Blaszczynski, 1997; Band, 1989a,b) can produce segmented images with the highest spatial homogeneity and therefore readability. Band (1989b) differentiates two general approaches to hierarchical classification; a bottom up agglomeration of pixels based on hydrological connectivity (the hikers view) and a top-down segmentation (the pilots view) based on identification of a topological network of inter-connected divide and stream networks which act as boundaries at successively finer scales. In a top-down classification, segmentation is initiated at the top level (coarsest resolution) and proceeds to successively finer scales. Each level of the hierarchy relates to a certain scale of feature or process and segmentation at every level gives context to, and drives, segmentation of the level below (Weibel and De Lotto, 1988). Hierarchical classifications not only produce more spatially homogeneous images, they also permit landform entities to be classified at various scales simultaneously, thereby addressing the common problem of multi-scale variation in most terrain data sets.

1.3.3 Development and characterization of soil-landscape models

Soil mapping is widely acknowledged to be aided by, and based on, identification and analysis of soil landform units (Swanson, 1990a) or soil landscapes (Swanson, 1990b; Northcote, 1984). In fact, the soil-landscape model is recognized as the guiding paradigm for soil survey in the USA (Hudson, 1992, Arnold, 1979a,b). The basic principal underlying soil-landscape mapping is that the location and distribution of soils in the landscape follow a predictable pattern related to the shape of the landforms and relative position (crest, footslopes, toeslopes) on the landform (Hudson, 1992; Arnold, 1979a,b; Miller et al., 1979). Geomorphological position has been shown to influence horizonation and soil attributes (Moore et al, 1993; Gessler et al., 1996) Hydrological and erosional processes occurring in landscapes have been shown to be related to topographical attributes such as elevation, slope, aspect, catchment area, profile and plan curvature (Moore et al., 1988, 1991, Pennock and De Jong, 1987; Pennock et al., 1987 1994; Zebarth and De Jong, 1989a,b; Zebarth et al., 1989a, Martz and De Jong, 1991). Crop productivity has been related to landscape position and landscape properties (i.e. slope gradient and length) (Jones et al., 1989; Goddard et al., 1996; Tomer et al., 1997) as have individual soil properties (Moore et al., 1993, Walker et al., 1968; Gressler et al., 1996).

Soil survey maps, reports and digital databases have traditionally done a poor job of describing and reporting on the properties of the landform component of soil-landscape units (Swanson, 1990a,b; Grigal, 1984; Indorante et al., 1996). Map unit descriptions

have emphasized soil classification and morphology (Swanson, 1990a) despite widespread recognition of the importance of landform and landform position in controlling the spatial distribution of soils, soil properties and interpretations of land use.

Indorante et al. (1996) reiterated the importance of improving descriptions of the relationships between soils and landform position and of the geomorphological characteristics of soil-landscape units in future soil survey documents and digital databases. Improved descriptions of soil landscape relationships were viewed as critical to providing users with an ability to identify and appreciate site-specific soil variability.

Some work has been done by individual innovators wishing to demonstrate potential applications of DEM data (Pennock and De Jong., 1987; Zebarth and De Jong, 1989a,b; Pennock et al., 1987, 1994; Mulla, 1986; Franklin, 1987; Lanyon and Hall, 1983a,b; Gessler et al., 1996). However, the application of existing methodologies to characterize soil-landscape models is not a common practice and has never been applied in a standard operational mode to large (e.g. province wide) areas.

1.3.4 Soil-landscape models and tacit knowledge

Hudson (1992) has observed that creation and use of soil landscape models has one major weakness, that being an extreme reliance on tacit knowledge. Soil scientists learn to place a large number of individual soil delineations into a more limited number of similarity units or natural groups (Hudson, 1992). This grouping forms the basis of the soil-landscape paradigm. Unfortunately, the concepts of the paradigm have not been explicitly stated or written down, but have resided mostly in the minds of perceptive, experienced soil surveyors (Hudson, 1992).

The challenge is therefore to abstract tacit knowledge regarding soil-landscape models and to express it quantitatively, formally and linguistically. One such example is provided by Skidmore et al. (1991) who developed expert system rules relating soil landscape units to GIS data layers portraying soil wetness and topographical position. The rules were based on heuristics and represented the "feeling" or "knowledge" of experts, although the authors expressed a preference, in an ideal situation, for rules based on statistical evidence. Since environmental relationships can rarely be expressed with absolute certainty (true or false), the rules were formulated in terms of estimated probabilities lying on a continuum between true (probability of 1) and false (probability of 0) (Skidmore et al., 1991). For example, the probability that there is a very dry gully (VDG) landform position given that the residual crest (RC) soil-landscape unit occurs was estimated by an expert to be 0.4.

The expert system devised by Skidmore et al. (1991) inferred the most probable soil-landscape unit at a given cell using Bayes' theorem of evidential reasoning. The approach of Skidmore (1989b) and Skidmore et al. (1991) demonstrated a procedure to capture local tacit knowledge of soil-landscape relationships and express it as

quantitative rules in the form of estimated probabilities. Formal, quantitative description of the distribution of soils by landform element would represent a significant improvement of current soil-landscape models and would capture some of the important tacit knowledge that is currently not recorded.

2. MATERIALS AND METHODS

2.1 Description of the study area

The procedures were developed, applied and evaluated for a single study area (the Lunty site) located in the Parkland Ecoregion, near the town of Forestburg about 200 km south east of Edmonton, Alberta. The site (Figure 2) occupies an area of about 700 m by 800 m approximating the dimensions of a quarter section, which is a typical farm-scale management unit in western Canada.

Figure 2. Location of the Lunty study site

The topography is fairly typical of cultivated morainal landscapes in the Black soil zone. It is classified (MacMillan, 1994) as a low to moderate relief hummocky till plain. Maximum local relief is 8 m with elevations ranging from 721 to 729 m asl. Slope gradients average 2-5 percent for most upper convex portions of the landscape. Few slopes are steeper than 6-9 percent. Slope lengths average 75-150 m and range from 40 to 400 m. The site has a closed, non-integrated, drainage pattern typical of hummocky topography and contains many shallow depressions that exhibit seasonal ponding. The depressions range in size from 0.1 to 9.0 ha and are slightly convex with slope gradients of 0-2%.

The digital elevation model (DEM) for the study area consists of a regular matrix of 161 rows by 140 columns with a horizontal grid sampling interval of 5 m. The initial vertical resolution was 0.001 m but this was rounded to 0.1 m to reduce noise in the data set. The DEM was produced by Alberta Department of Environmental Protection using an analytical stereo plotter. It was based on specially flown 1:3,500 scale aerial photographs taken in October, 1987. Registration and rectification of the aerial photography used six accurately surveyed ground control targets laid out in the field to coincide with the date of aerial photography.

Detailed grid and transect soil mapping conducted for previous research (MacMillan, 1994) revealed the presence a wide variety of soils and a strong relationship between soils and landform position. The observed distribution of soils is interpreted mainly in terms of topographical control of the movement of water over the soil surface and through the soil profile. A predictable catena or toposequence emerged from analysis of the detailed site data (see Appendix 1).

The Lunty site provided an optimum combination of a readily available, high resolution DEM and detailed soils data appropriate for developing and evaluating the procedures documented in this bulletin. Both the soil assemblage and the hummocky morainal landscape are common within the agricultural portions of Alberta.

Table 1. Terrain derivatives computed to characterize landforms and segment into facets

Derivative	Abbr	Reason for Interest	Source of Algorithm
Slope Gradient	SLP	A major criteria used in existing qualitative systems of landscape classification, single most important variable for most models or decision rules for evaluating soil problems	Pennock et al. (1987)
Aspect	ASP	A commonly measured and reported terrain derivative. The magnitude and frequency of variation in aspect might prove useful in differentiating landscape with uniform orientations (i.e. inclined) from those with preferred orientations (i.e. ridged) from those with chaotic orientations (i.e. hummocky)	Eyton, 1991 Eyton, 1995
Absolute Local Relief	REL	A major criteria used in existing qualitative systems of landscape classification. Both total absolute relief and the frequency distribution of local absolute relief can be used to differentiate high relief from low relief landscapes.	Original based on Meijerink, 1988
Down-slope Curvature	DCV	Down-slope (or profile) curvature identifies areas which tend to shed versus accumulate runoff. In general, shoulders tend to be convex and toe-slopes concave in profile. Curvature has been used in previous attempts to automatically classify landscapes ((Pennock, Zebarth and de Jong, 1987)	Eyton, 1991 Eyton, 1995
Cross-slope Curvature	XCV	Cross-slope (or plan) curvature identifies areas which tend to shed versus accumulate runoff. In general, divergent areas are convex and convergent areas concave across slope. Curvature has been used in previous attempts to automatically classify landscapes ((Pennock, Zebarth and de Jong, 1987)	Eyton, 1991 Eyton, 1995
Total or Maximum Slope Length	LEN	A major criteria used in existing qualitative systems of landscape classification. Slope length is an important input variable for many models (i.e. USLE)	Original,
Up-slope Length	LUP	Upslope length provides a measure of the relative energy of surface runoff arriving at any given point in the landscape. It also provides a measure of the position in the landscape of a given cell relative to the nearest crest (i.e. its down-ness)	Original
Down-slope Length	LDN	Down-slope length provides a measure of distance any material has to flow from a given cell to reach the terminus of a flow path (i.e. its dispersal distance) It also provides a measure of the position in the landscape of a given cell relative to the nearest depression (i.e. its up-ness)	Original but similar to that of (Martz and deJong, 1988)
Relative slope position	PUP	This is a new measure of relative slope position. It provides a measure of each grid cell's context in the landscape (its relative position upslope vs downslope). It is computed by dividing the distance from each grid cell to a flow terminus (its downslope length) by the maximum slope length to each watershed It is expressed in % as percent upslope from a flow path terminus.	Original but similar in concept to that of (Skidmore et al., 1991)
Watershed Size or Density	CAT	Not a widely computed or used measure to date. Size of drainage area can be interpreted as an indication of degree of integration (or disruption) of surface drainage as well as the size (scale) of landscape units. Large watersheds will be characteristic of large landforms with integrated drainage, Small watersheds should indicate smaller landforms with disrupted drainage and frequent slope changes.	Computed using Watersh (van Deursen and Wesseling, 1992)

2.2 Terrain attributes of potential interest and use

The criteria used to identify potential terrain attributes of interest (Table 1) included:

1. Were the terrain attributes meaningful as general morphometric descriptors of landscapes?
2. Were the terrain attributes commonly used as input for landform classifications, models or decision rule algorithms?
3. Were the terrain attributes likely to be useful for automatically segmenting landscapes into component landform facets (i.e. crests, toeslopes,)?
4. Did algorithms exist for computing the terrain attributes and could they be implemented feasibly and rapidly for use in the present project?
5. If algorithms did not currently exist for potentially useful attributes, was it feasible to create new algorithms and write computer programs to implement them for use in the current project?

Slope gradient and slope length were considered important because of their widespread use in evaluations of landscape behavior such as sensitivity to erosion and suitability for agriculture. Relative slope length in the upslope and downslope directions was judged to be of interest mainly because of its potential for helping to establish the relative "up-ness" or "down-ness" of a particular grid cell thus placing it in its proper spatial context or landform position. Topographic curvatures in both the cross-slope (plan) and down-slope (profile) directions were of interest because of their previously reported utility for identifying and classifying landscape elements. (Pennock and de Jong, 1987; Pennock, Zebarth and de Jong, 1989a). Relative relief was of interest because it has been used as a differentiating criteria in existing qualitative landform classification schemes (ECSS, 1987b) and was judged to be essential for describing and differentiating landscapes on the basis of relief.

Aspect was proposed for investigation in the expectation that it might help to differentiate landscapes with preferred orientations (i.e. ridges, dunes, inclines) from those with no preferred orientations (i.e. hummocky, pitted, possibly undulating). The absolute value of aspect was not considered as important as the frequency and scale of variation in aspect in a given landscape. A number of measures of watershed size, density and connectivity were proposed as potentially useful for evaluating the degree of integration versus disruption of surface drainage in a given landscape. It was thought these might prove useful as indicators of the extent of any landscape that contributed to off site flow by processes such as runoff, erosion and transport of non-point source pollutants.

Slope gradient and aspect were considered as measures of terrain orientation, down-slope and across-slope curvature were considered to be measures of terrain shape, and total slope length, absolute relief and wavelength (horizontal distance from trough to trough) were used as measures of terrain scale. The attributes up-slope length,

down-slope length and relative slope position were used as measures of landscape context. Finally, the number and size of local watersheds were used to differentiate simple landscapes with integrated drainage patterns from complex landscapes with non-integrated drainage.

Each of the terrain attributes (Table 1) was computed for the example site and analyzed in terms of its utility as a morphometric measure for characterizing and differentiating landscapes in the Canadian prairies. The analysis sought to establish the meaning of the term and to clarify what attribute of the landscape was measured and described by each derivative. Technical and conceptual concerns relevant to each derivative were identified and discussed. These included, what was being measured, why it was being measured and techniques and algorithms available for calculating the derivative.

2.3 Programs and algorithms used to compute morphometric indices

Morphometric analysis of the digital elevation model was accomplished using custom written programs implemented in an xbase database programming language (**FoxPro for Windows™**).

The database programming environment was adopted because it greatly facilitated implementation of some programs that relied on sorting the DEM to permit processing of grid cells in topological order, by elevation and along flow paths. It also provided a single environment within which to process the DEM and compute all terrain derivatives. No other single package or set of programs provided a full set of programs for computing all terrain derivatives of interest. Initial use of a variety of programs provided in several public domain packages required considerable reformatting and transfer of data. Additionally, the database programming approach, while significantly slower than most other available programs, presented no limitations in terms of the size of DEM data sets that could be processed. The database approach also greatly facilitated input and output, including production of custom reports linking text and graphics to illustrate soil-landscape models.

Many of the algorithms used to compute the terrain derivatives used to characterize landform morphology and to segment (classify) landscapes into landform elements were re-implementations of previously described algorithms (Table 1). Several of the measures of terrain morphometry were based on original algorithms.

The procedure used to classify the landscape into component land facets drew on previous work described by Pennock et al. (1987) and Skidmore et al. (1991). The procedures used to capture tacit knowledge in order to assign soils to landform facets were similar to an approach described by Skidmore at al. (1991) and Skidmore (1989b).

2.4 Sequence of activities

The flow chart of activities (Figure 3), indicates that the first action was to identify a number of landform attributes that had clear potential to provide useful and quantitative information about landform morphology. This was followed by quantitative analysis to define each attribute in terms of its range, extent and location at the example site. It was assumed that detailed digital elevation data (DEMs) from a representative site can be used to establish the principal morphological attributes for a particular landform type. Calculation of the terrain derivatives and application of selected derivatives to segment landscapes into landform elements followed a sequence of activities similar to that described by Weibel and De Lotto (1988) and Franklin (1987).

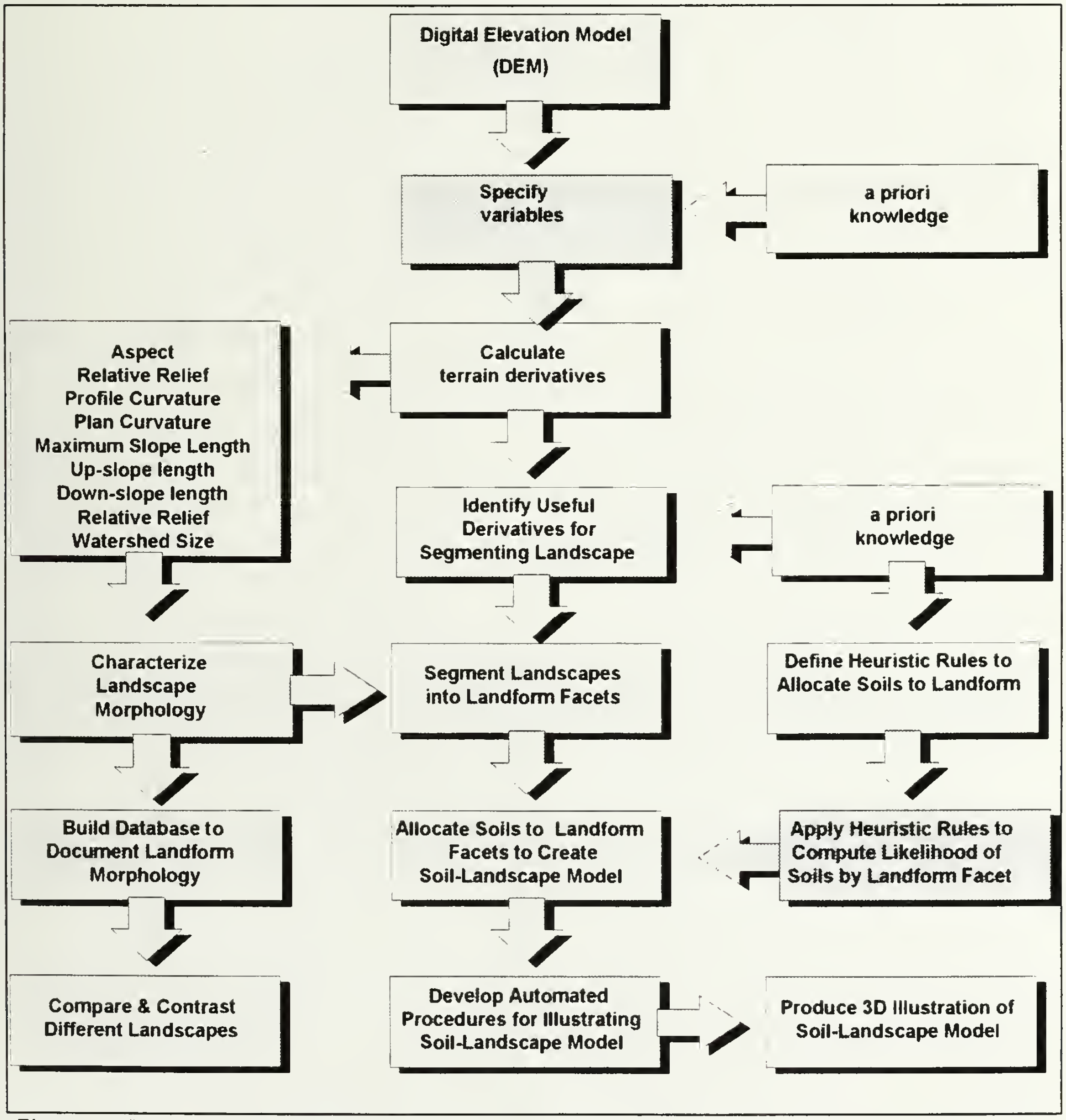


Figure 3. Flow chart of activities followed to characterize and segment the example landscape and build and illustrate an example soil-landscape model

3. MORPHOMETRIC CHARACTERIZATION OF LANDSCAPES

3.1 Results for 10 attributes computed for a single test site

The DEM for the selected test site was processed to calculate all 10 of the terrain derivatives listed in Table 1. The algorithms used to compute each derivative are identified in Table 1 and discussed briefly below.

A standard, single page, template was designed to facilitate a consistent and uniform presentation and discussion of each of the 10 terrain derivatives. The template consists of an illustration and concise definition of the derivative of interest, a short discussion of algorithms available for computing the derivative and identification of the actual algorithm used to compute each derivative. At the bottom of each page is a 3D perspective view depicting the spatial distribution of the computed terrain derivative in the example landscape. A graph immediately to the right of each 3D diagram illustrates the cumulative frequency distribution for each variable (solid line) as well as the proportion of the total site (bars) falling into each of a number of defined classes. Wherever possible, widely used existing classifications (i.e. slope, curvature) were used to define the class limits for the bar graphs. Arbitrary class limits were defined for several terrain derivatives for which no existing class definitions were available.

The 5 by 5 m horizontal grid spacing of the DEM for the example site was judged to adequately capture the variation in the terrain of the main topographic features of interest. A different grid spacing might be appropriate for other sites or other types of landforms but, in general, our experience has been that horizontal grid spacings of 10 m or less are required to capture much of the subtle variation in terrain for glaciated landforms in the prairies of western Canada (see discussion in section 3.2).

All 10 terrain derivatives were not used to define landform segments in the subsequent efforts to classify landforms and allocate soils to landform segments. Those derivatives not used to segment the landform are still considered to be valuable for other potential applications. They serve the objective of characterizing significant attributes of the landform but are not required for the specific purpose of landform segmentation.

Following are the results of computing the ten selected landform attributes for the selected test site.

3.1.1 Slope gradient

Definition of slope gradient

Slope gradient (Figure 4) is defined (Eyton, 1991) as the maximum rate of change of elevation in the down-slope direction (dz/dx).

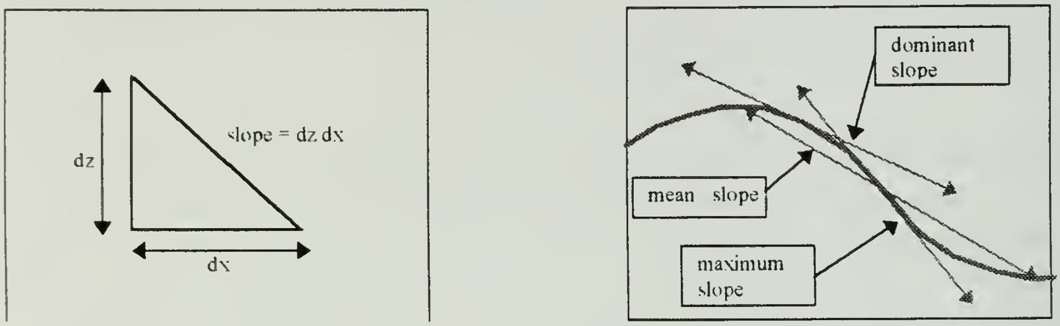


Figure 4. Definition and interpretation of slope gradient

Algorithms for computing slope gradient

Despite the rather large number of algorithms that exist for computing slope gradient, there are really only two basic computational approaches (Eyton, 1991). The most commonly used fits a least squares polynomial or an exact fitting multiquadric equation to a portion of a DEM (usually a 3x3 neighborhood) and uses an analytical form of calculus to compute the derivatives (Eyton, 1991). Another approach uses a numerical approximation procedure of finite differences (Eyton, 1991) to compute rise/run in the E-W (row) and N-S (column) directions.

Slope gradient results for the test site

The results for slope gradient (Figure 5) use the analytical surface fitting approach as implemented by Martz (Pennock et al., 1987). Subsequent efforts may expand to investigate the relative merits of adopting the alternative numerical finite difference approach of Eyton (1991).

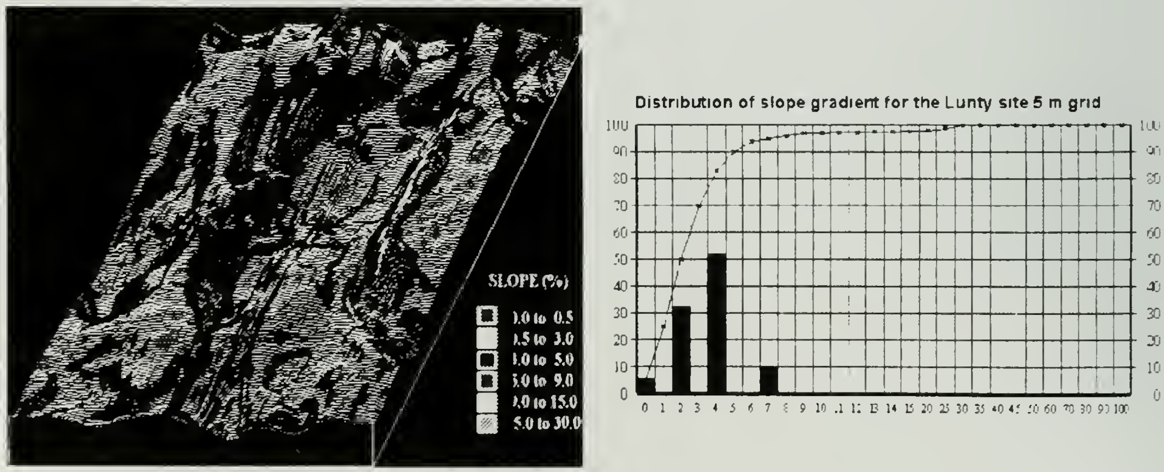


Figure 5. 3D illustration and histogram of slope gradient for the test site

3.1.2 *Slope aspect*

Definition of slope aspect

Slope aspect (Eyton, 1991) is the azimuthal compass bearing in degrees from north of the slope vector in the maximum downslope direction (Figure 6).

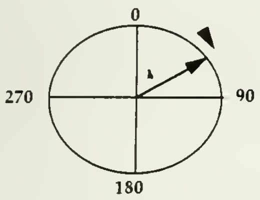


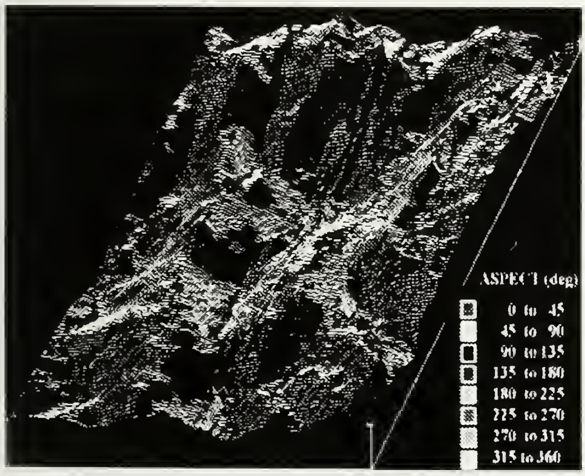
Figure 6. Illustration of the definition of slope aspect

Algorithms for computing slope aspect

As with slope gradient, there are two basic approaches for computing aspect; namely numerical methods based on finite difference calculations (Eyton, 1991) and analytical methods based on differential calculus (Zevenbergen and Thorne, 1987; Pennock et. al., 1987).

Slope aspect results for the test site

The numerical method (Eyton, 1991) was used to compute slope aspect for the example site (Figure 7). It involves computing the slope in x (E-W) and the slope in y (N-S) and from these determining the gradient and azimuthal direction of the resultant slope vector using the Pythagorean theorem where r = SQRT(x^2 + y^2). The method fits a planar surface exactly to the 4 data points located orthogonally N-S and E-W of the center point of a 3 x 3 window in a raster DEM.



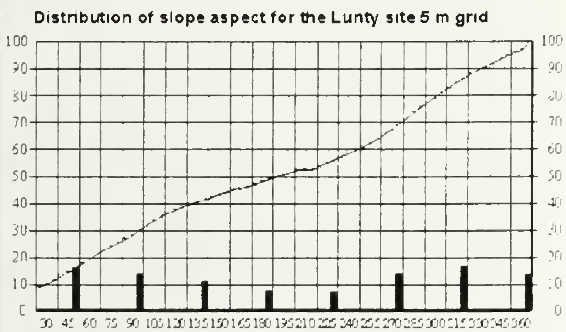


Figure 7. 3D illustration and histogram of slope aspect for the test site

3.1.3 Absolute local relief

<u>Definition of absolute local relief</u>

Relief is a measure of the scale of the landscape in the vertical dimension. Manual systems of landform classification (Meijerink, 1988) rely on analysts to estimate the maximum local relief. This is generally considered to be the vertical difference in elevation between a crest and its associated trough (see Figure 8).

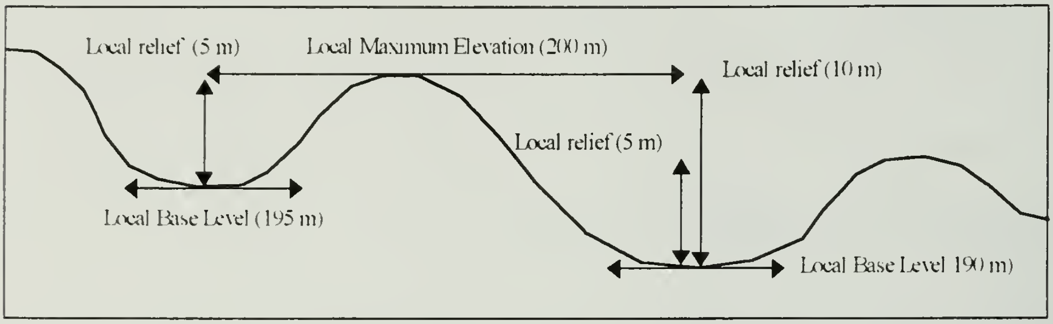


Figure 8. Illustration of the definition of local relief

<u>Algorithms for computing absolute local relief</u>

Relief is most often computed digitally (Franklin, 1987; Weibel and De Lotto, 1988) as a measure of the maximum absolute difference or standard deviation of *n* elevation values within a moving window of fixed dimensions (usually 3x3). The original algorithm used for the present exercise computed the local relief of each grid cell in terms of a local base level taken as the pit centre of the local depression (Figure 9). Absolute local relief was measured in metres above the local base level. Relief classes (Figure 9) simply reflect increments of 0.5 m above base.

<u>Absolute local relief results for the test site</u>

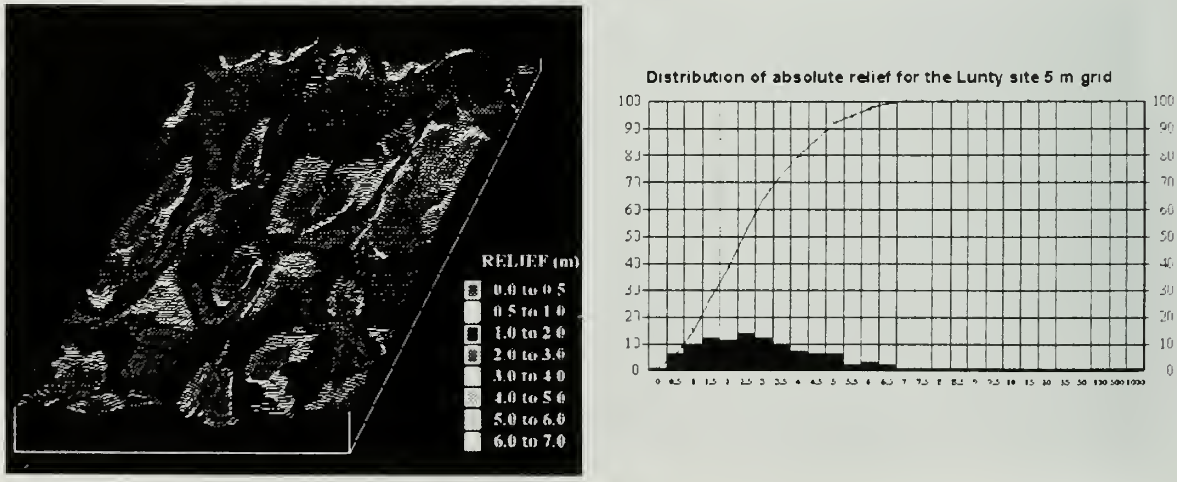


Figure 9. 3D illustration and histogram of absolute local relief for the test site

3.1.4 Down slope (profile) curvature

Definition of profile curvature

Curvature is defined (Eyton, 1991) as the first derivative of slope (the rate of change of slope) or the second derivative of elevation (the rate of change of the rate of change of elevation).

Geomorphologic convention considers convex surfaces to be positive and concave surfaces to be negative. Down slope curvature is a directional curvature calculated along a line parallel to the maximum downslope azimuth. It is often referred to as profile curvature (Pennock et. al. (1987) as it corresponds with the view associated with a cross sectional profile of the landscape (Figure 10).

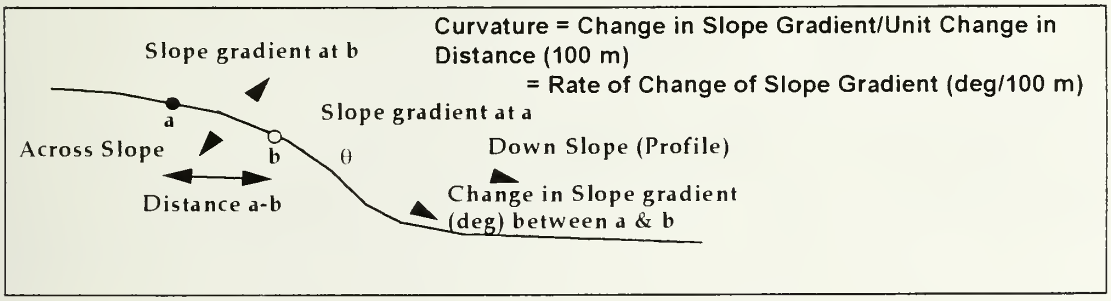


Figure 10. Illustration of the definition of down slope & across-slope curvatures

Algorithms for computing profile curvature

As with slope and aspect, both numerical and analytical methods exist for computing profile (and plan) curvature. For initial testing purposes, two sets of analytical algorithms (Pennock et al., 1987; Zevenbergen and Throne, 1987) and one numerical algorithm (Eyton, 1991) were implemented and run against the test data set. The numerical algorithm was judged to be more robust and was used to produce the results reported here (Figure 11).

Profile curvature results for the test site

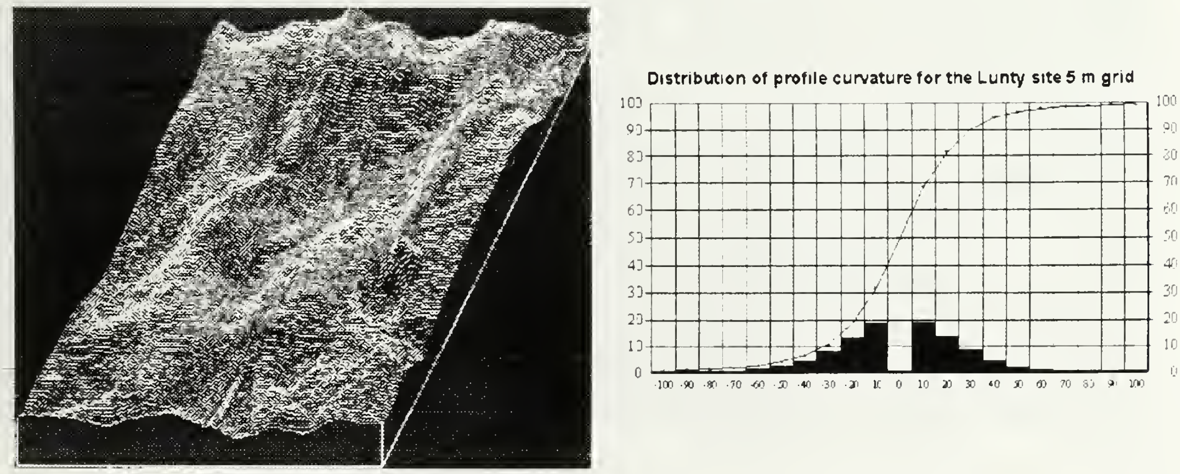


Figure 11. 3D illustration and histogram of profile curvature for the test site

3.1.5 Across slope (plan) curvature

Definition of plan curvature

Across slope curvature (Figure 12) is a directional curvature calculated along a line perpendicular to the maximum downslope azimuth. It is often referred to as plan curvature (Pennock et. al., 1987).

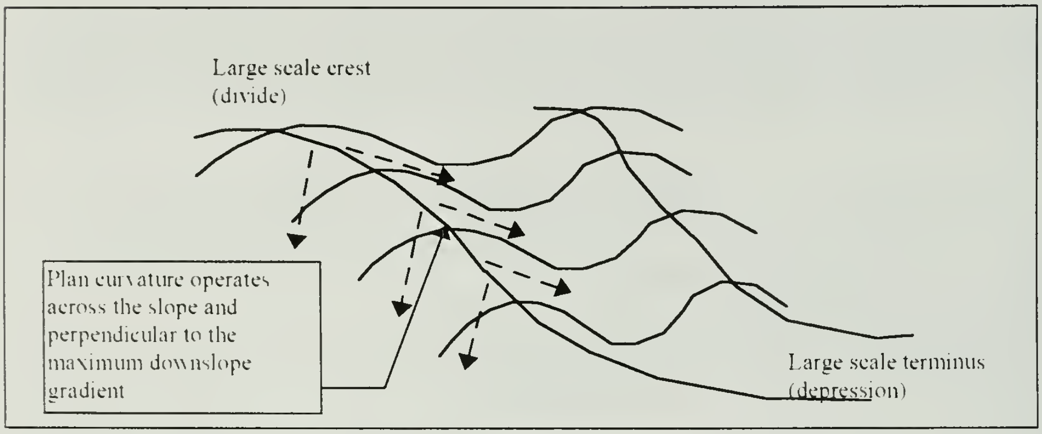


Figure 12. Illustration of the definition of across slope or plan curvature

Algorithms for computing across slope curvature

As with down slope curvature, both numerical and analytical methods exist for computing across slope (plan) curvature. For initial testing purposes, two sets of analytical algorithms (Pennock et al., 1987; Zevenbergen and Throne, 1987) and one numerical algorithm (Eyton, 1991) were implemented and run against the test data set. The numerical algorithm was judged to be more robust and was used to produce the results reported here (Figure 13).

Plan curvature results for the test site

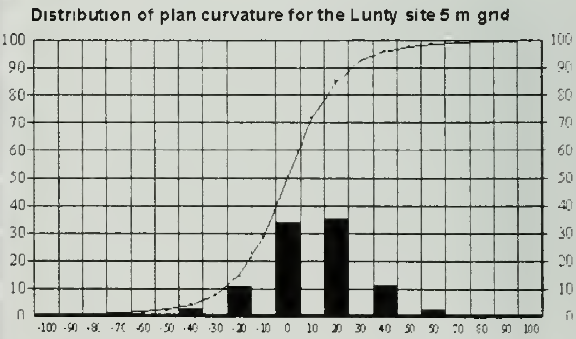


Figure 13. 3D illustration and histogram of plan curvature for the test site

3.1.6 Total or maximum slope length

<u>Definition of total slope length</u>

Total slope length (Figure 14) is defined, for the present exercise, as the total linear distance in metres from a grid cell with no other grid cells upslope of it (a divide grid cell) to the lowest grid cell in a local watershed. This is the point at which a flow path originating at the initial divide cell terminates.

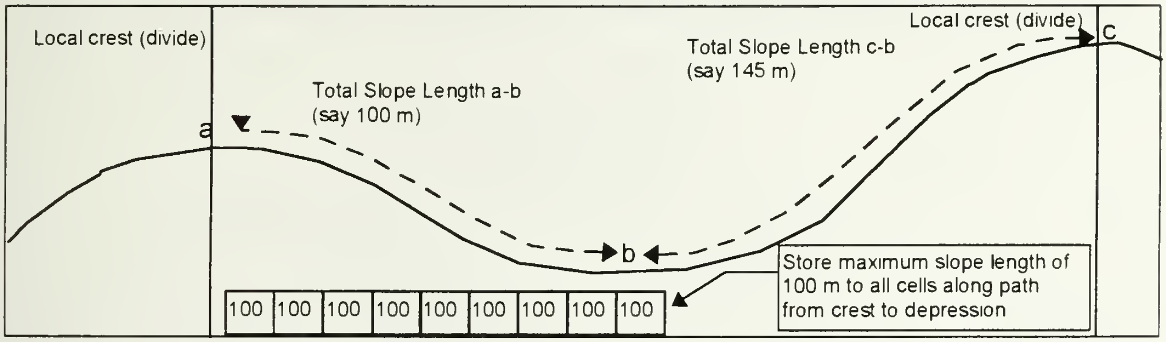


Figure 14. Illustration of the definition of total maximum slope length (metres)

<u>Algorithms for computing total slope length</u>

The algorithm used to compute slope length is based on dispersal distance as computed by Martz and de Jong (1988). This algorithm goes to every grid cell in turn and traces down its flow path to its terminus. The total number of cells traversed from start cell to flow terminus is multiplied by the unit length of each grid cell in metres to compute the total length of the slope run (Figure 15). This length is stored for every cell along the flow path for which a larger slope length value has not already been computed and stored.

<u>Total slope length results for the test site</u>

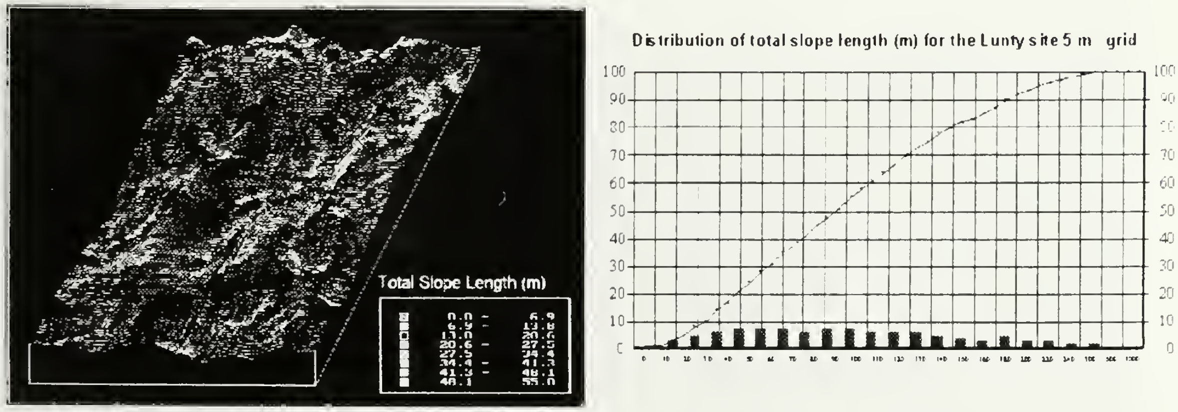


Figure 15. 3D illustration and histogram of total slope length for the test site

3.1.7 Maximum and relative upslope length

Definition of upslope length

For the present study, absolute upslope length is defined as the distance in metres upslope from a given grid cell to the highest elevation divide cell which is connected to the cell in question by a steepest descent flow path (Figure 16). Relative upslope length is defined as the ratio between the absolute upslope length in metres and the sum of upslope length plus downslope length in metres. It is multiplied by 100 and expressed in dimensionless terms as a percent.

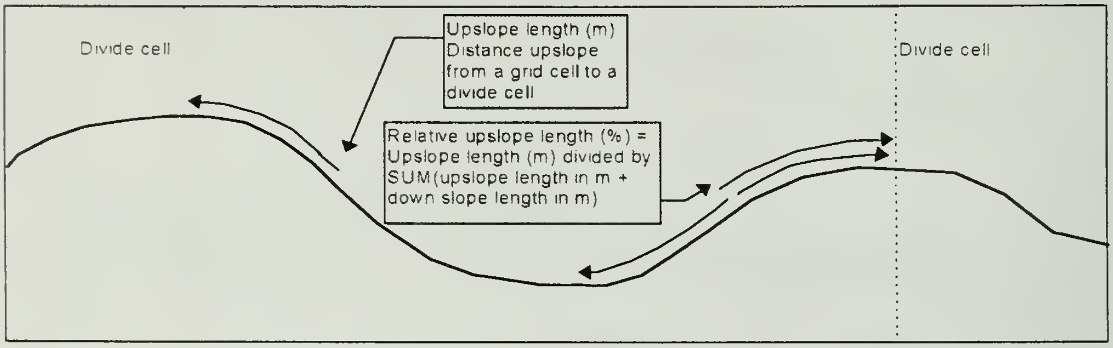


Figure 16. Illustration of the definition of absolute (m) and relative (%) upslope length

Algorithms for computing upslope length

The algorithm adopted for the current study is similar to that described by Martz and de Jong (1988). It traces down flow paths from nominated divide cells (upslope area = 0) and stores the length in metres of the longest flow path to pass through each cell to that cell.

Upslope length results for the test site

Absolute upslope length (Figure 17) provides a measure of the length of the flow path upslope from a given cell or, viewed in reverse, the linear distance that a cell is downslope from a crest.

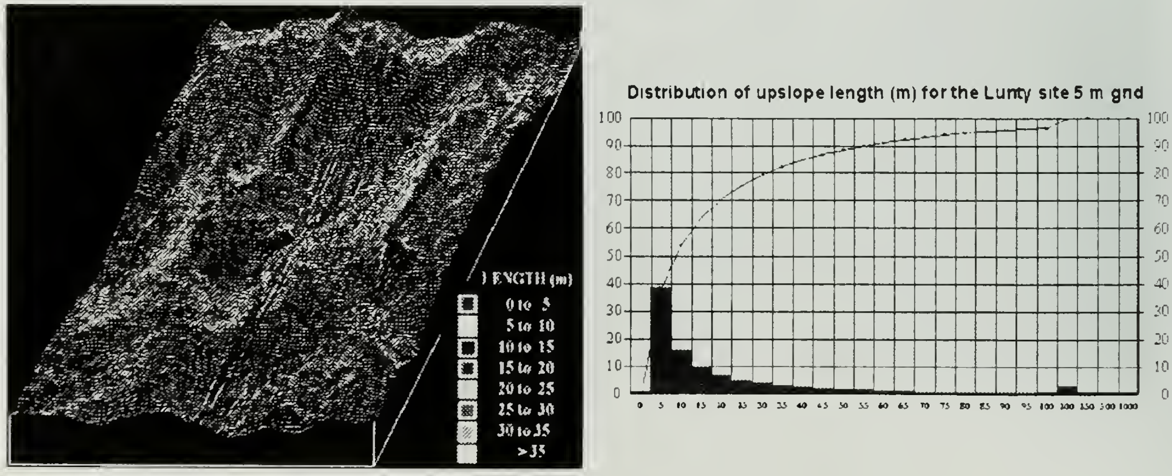


Figure 17. 3D illustration and histogram of absolute upslope length for the test site

3.1.8 *Maximum and relative downslope length*

Definition of downslope length

Absolute downslope length is the conceptual opposite of upslope length. For the present study, it is defined as the absolute distance in metres along a flow path from any cell to the pit cell at which flow terminates (Figure 18). It is identical to downslope dispersal distance as defined by Martz and de Jong (1988). Other possible definitions of downslope length could be based on terminating flow at the point of inflection in the foot slope or as soon as the slope gradient fell below a certain threshold value. These were judged to be unnecessarily complex for the present study.

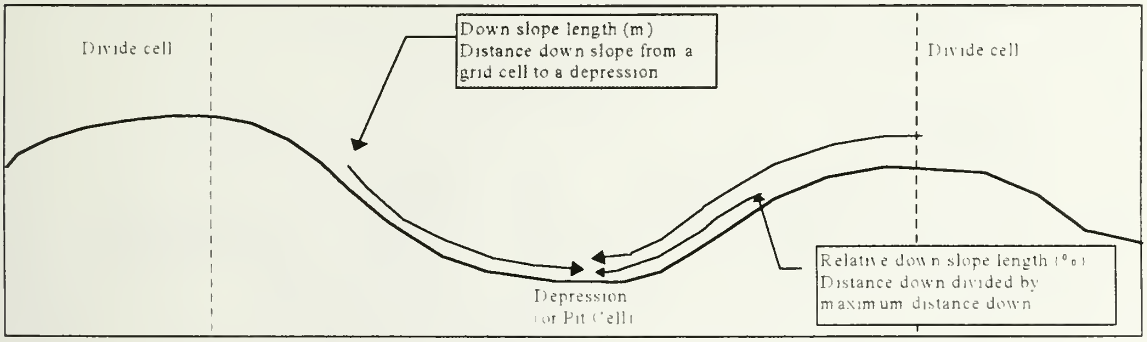
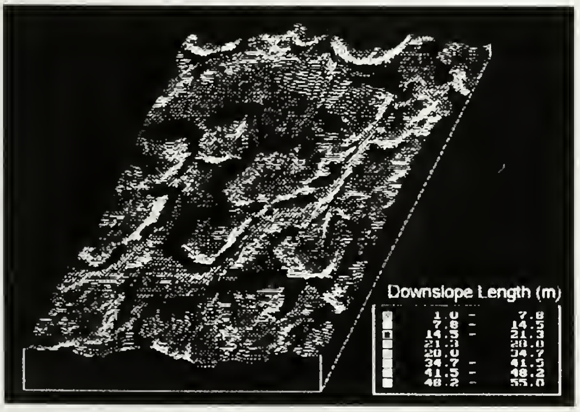


Figure 18. Illustration of the definition of absolute (m) and relative (%) downslope length

Algorithms for computing downslope length

The algorithm used to compute downslope dispersal distance is essentially that of Martz and de Jong (1988). A few modifications were introduced by implementing the algorithm in a data base programming environment. The implemented procedure initiates flow only for grid cells with no upslope cells (i.e. divide cells). Each flow path starts at a divide cell and traces down until it terminates at a pit cell (Figure 19). Concentric circles are defined around each pit centre cell.

Downslope length results for the test site



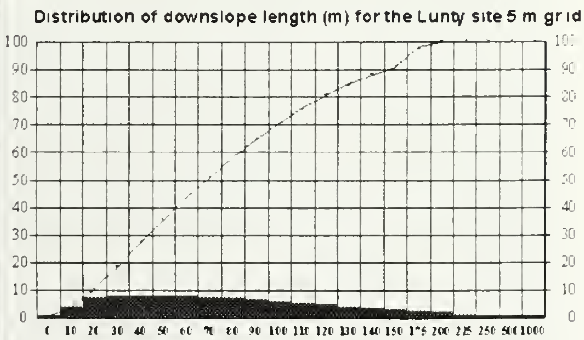


Figure 19. 3D illustration and histogram of absolute downslope length for the test site

3.1.9 *Relative slope position*

Definition of relative slope position

Relative slope position is defined, for the present exercise, in terms of relative relief (Figure 20). It is computed as the ratio of the difference between the elevation of a grid cell and the elevation of the lowest cell in a watershed (the pit cell) divided by the maximum difference in elevation between the highest cell in the watershed and the lowest (the pit cell). The ratio is multiplied by 100 and expressed as a percent as in percent upslope from a pit centre.

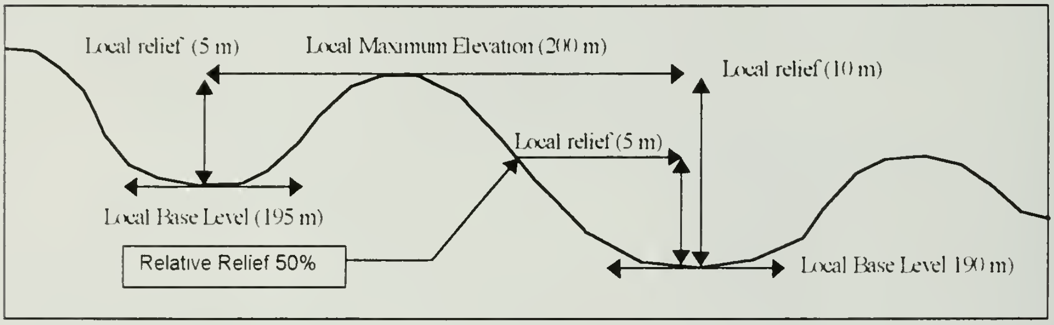
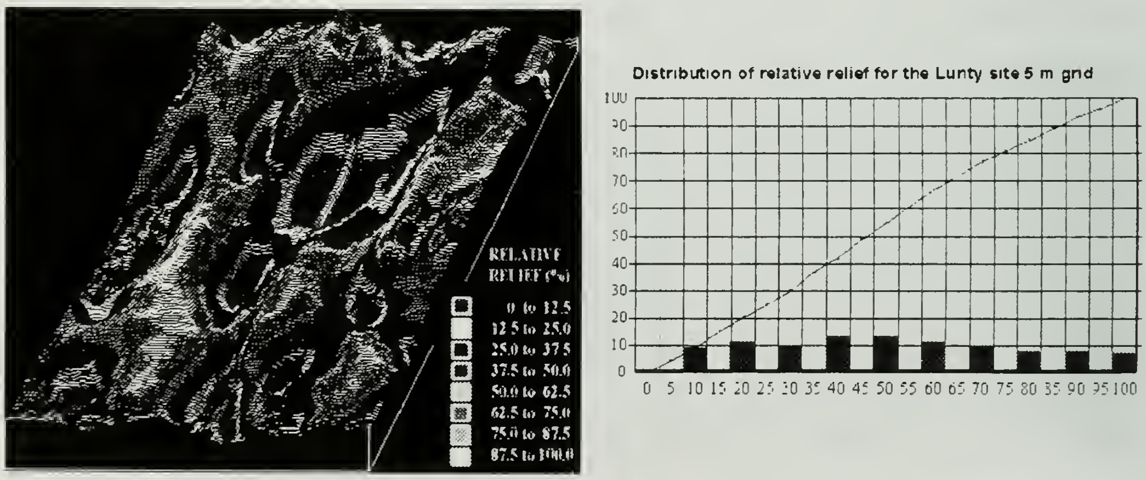


Figure 20. Illustration of the definition of relative slope position expressed as percent upslope

Algorithms for computing relative slope position

The most widely cited algorithm for computing relative slope position (Skidmore, 1990) is based on determining the Euclidean distance from each cell to the nearest channel cell and ridge or divide cell.. The present exercise chose to identify a single base level (a pit cell) and a single maximum elevation for each small depressional watershed and to express slope position in terms of elevation above the base level relative to the maximum elevation difference (Figure 21).



Relative slope position results for the test site

Figure 21. 3D illustration and histogram of relative slope position for the test site

3.1.10 *Watershed size and density*

Definition of a local depressional watershed

Many landscapes in glaciated regions such as Alberta display non-integrated drainage with local flow of surface water accumulating in small, undrained depressions (Figure 22). The sum of all grid cells that contribute flow to a local depression can be thought of as constituting a local depressional watershed (Figure 22). The degree to which surface water flow in a landscape is involved in internal flow into local undrained depressions versus external flow into continuous stream channels can be used as a measure of the degree of integration (or disruption) of surface drainage in the landscape.

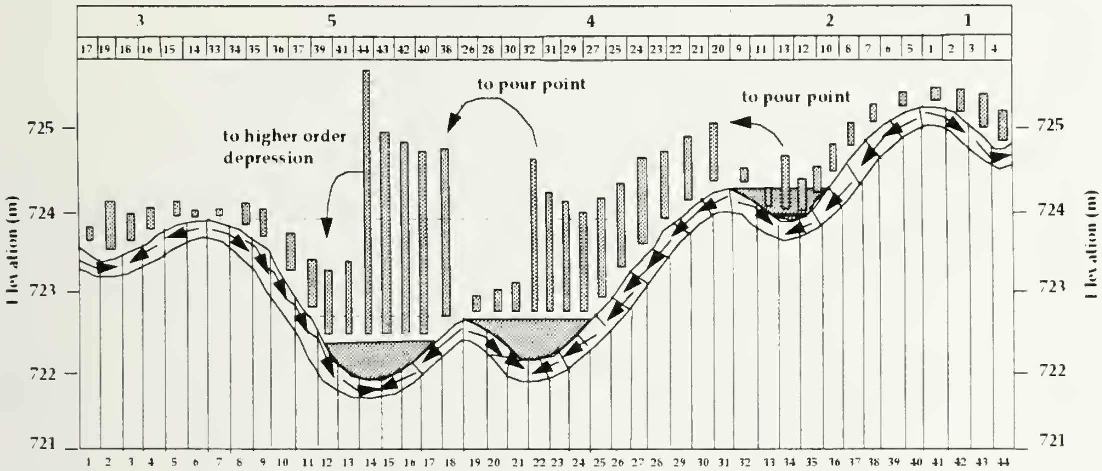
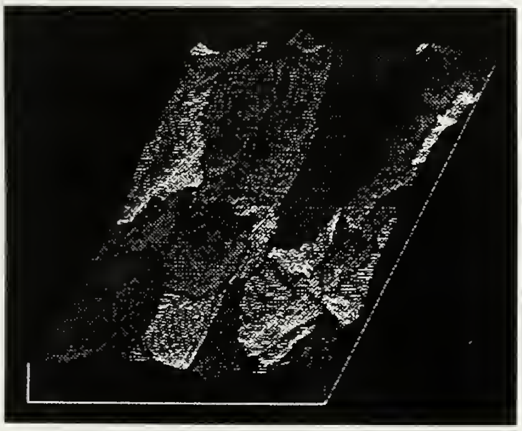


Figure 22. Illustration of the definition of a local depressional watershed

Algorithms for computing local watersheds

The ***Watersh*** module of the public domain GIS ***PC-Raster*** (van Deursen and Wesseling, 1992) was used to compute and document the location and extent of local depressional watersheds. The size and location of depressional watersheds at the example site (Figure 23) indicates that 80% of local runoff will remain on site and only 20% will flow off-site.

Local Watershed results for the test site



Percent off-site drainage:	20%
Total number of watersheds:	59
Average size of watersheds:	0.95 ha
Density of watersheds:	1.05 per ha.

Figure 23. 3D illustration of local watersheds for the test site

3.2 Issues related to morphometric analysis

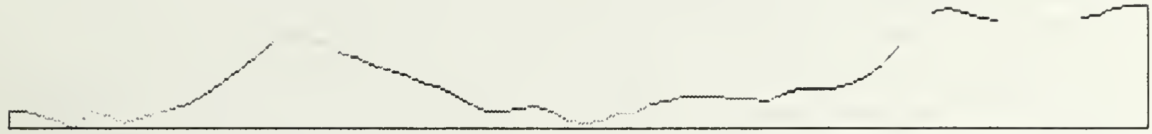
The systematic procedures used to analyze the digital elevation data and the quantitative morphometric statistics so produced are assumed to be correct and to accurately reflect the terrain characteristics of interest. Users of quantitative morphometric data should be aware that this is not always the case. Quantitative measurements of landscape morphology can be misleading due to various limitations in the data and the methodologies used to process the data.

3.2.1 Effect of grid size on terrain representation

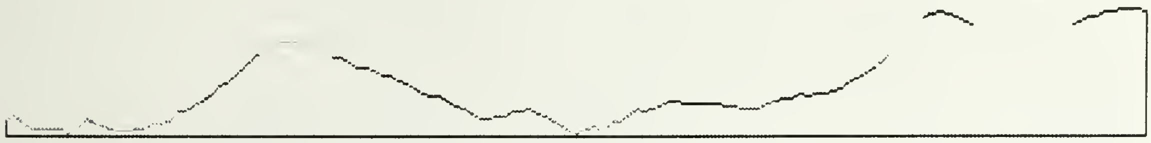
Perhaps the greatest single source of error in computing terrain derivatives arises from incorrect matching of the sampling dimensions of a regular gridded DEM to the dimensions of the landscape features of interest (Figure 24). This problem has been recognized since the earliest efforts to compute morphometric measures from gridded elevation data (Strahler, 1956) but it is often overlooked. Many studies have utilized available DEMs of inappropriate resolution and have consequently computed terrain derivatives that were not representative of actual terrain conditions (Neiman et al., 1987). Weible and De Lotto (1988) suggested using semi-variograms or frequency analysis of the power spectrum to establish the grain, or longest significant wavelength contained in a topographic sample. They recognized the need to tailor the size of the sampling window to the fundamental textural elements of the topographic sample of interest and observed that selection of a minimum sampling interval for a DEM is dependent on the complexity of the study area topography (Weibel and De Lotto, 1988).

For the majority of glaciated landscapes in Alberta, we are most often interested in the local slope over distances (10-20 m) within which variations in elevation and slope are significant from the point of view of agricultural management of land. To that end, it is instructive to investigate the effect on degree of topographic detail and likely relevance of terrain derivatives computed using DEMs with different sampling intervals (Figure 24). The sampling resolution is determined by the horizontal grid spacing of the DEM and the vertical accuracy of the elevation data in the DEM. The horizontal sampling interval of a DEM (grid spacing) and its placement in space has a profound impact on the degree of detail with which variation in the terrain is captured and on the value of terrain derivatives (including slope) computed from the DEM (Figure 24). The vertical accuracy of the DEM, especially the relative vertical accuracy, also has an effect on computations of terrain derivatives including slope gradient.

The profiles in Figure 24 were generated by resampling the 5 x 5 m DEM for the study area. The profiles illustrate an E-W topographic cross section across a quarter section (700 m). The total vertical relief is 8 m. It can be seen that significant changes in slope direction and slope gradient occur over distances of less than 50 m and elevations of less than 1 m. At 10 m only minor irregularities with wavelengths less than 20 m are missed. Some topographic features of short wavelength and low relief are missed by

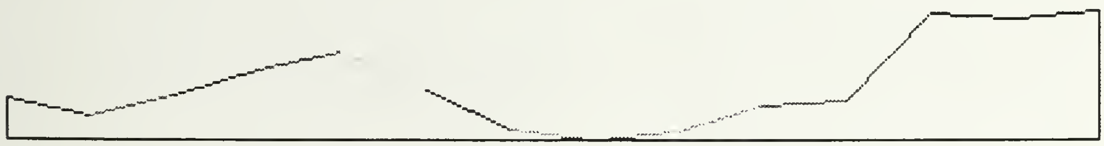


a) Cross sectional profile drawn using a 5 m sampling interval

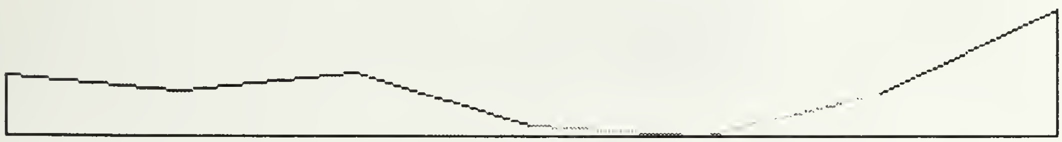


b) Cross sectional profile drawn using a 10 m sampling interval

c) Cross sectional profile drawn using a 20 m sampling interval



d) Cross sectional profile drawn using a 50 m sampling interval



e) Cross sectional profile drawn using a 100 m sampling interval

Figure 24. Illustration of the effect of sampling interval on representation of topography

the 20 m sampling interval, but all major landscape features are reasonably well represented. The original 5 x 5 m DEM captures all terrain variation of interest and may even contain some un-necessary detail. At the other extreme, the 100 m sampling interval does not adequately capture terrain variation at a level of detail required for most agricultural considerations and the 50 m interval misses some major terrain features.

It appears that a horizontal grid spacing of 5-10 m is optimum for representing this particular landscape. This is consistent with other studies (Wilson, 1996; Zhang and Montgomery, 1994; Quinn et al., 1995) which also found the optimum representation of terrain to be achieved by grid resolutions of 10 m or less. This spacing should be adequate for characterizing most other landscapes in Alberta, except for a limited number of very complex, low relief landscapes with significant changes in slope direction and gradient over very short distances (< 10 m). At the other extreme, landforms with very large amplitudes and wavelengths may be adequately characterized by DEMs with grid spacings of 50 m or even 100m.

It is suggested that a qualitative analysis of the grid spacing required to capture the terrain variation of interest should be conducted for each DEM of each new type landscape in order to ensure that the resolution of the DEM adequately captures the landform features of interest.

3.2.2 Effect of grid size on calculations of curvature

Calculations of profile and plan curvature for the example site DEM appeared to be strongly influenced by the grid spacing of the DEM (Figure 25). The problem was that, at the scale of the DEM data (5 m), most of the grid cells were computed to exhibit little or no curvature. Very few cells in upper landform positions displayed the expected convexity required to be interpreted as convex upper slope cells. Similarly, most cells in lower landform positions lacked the necessary profile concavity to be interpreted as lower slope or depressional cells.

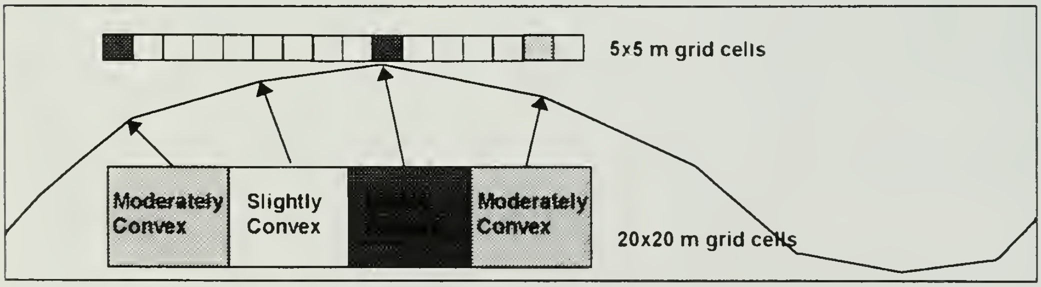


Figure 25. Illustration of the effect of grid size on computed curvature values

This apparent lack of curvature was significant, since the landform segmentation procedures of Pennock et al. (1987) use profile and plan curvature to classify

landscapes into landform elements. The original intention was to use these procedures to classify the example landscape into landform facets.

An experiment was conducted to examine the effect of successively larger DEM grid dimensions (10, 20, 50 m) on calculations of profile and plan curvatures. This resulted in calculation of more positive profile curvatures for a greater number of upslope cells and more negative profile curvatures for a greater number of downslope cells for DEMs with larger grid spacings. The majority of cells, however, retained relatively low values for both profile and plan curvature.

Analysis of the results suggested that most of the curvature in the study landscape occurred at discrete points of inflection and that landform segments between these points were relatively planar (Figure 25). As a consequence, when a DEM with a fine sampling resolution (5 m) was used to compute curvatures, most grid cells were located within short planar segments and were computed to have low curvature (Figure 25). As the grid size expanded, the likelihood of experiencing a significant change in slope between adjacent grid cells increased.

The planar nature of much of the DEM may possibly be a result of the numerical interpolation algorithm used to produce the regular DEM from the original photogrammetric sample data. Linear interpolation algorithms are likely to produce linear changes in elevation except at discrete locations where new points of significantly different elevation impact the local moving average. Interpolation algorithms that fit continuous analytical surfaces to all data points (i.e. multi quadric equations) are more likely to produce regular DEMs with a smoother and more realistic expression of profile and plan curvatures.

The concerns encountered with calculations of profile and plan curvature are representative of problems involved in using regular gridded DEMs and in fitting the DEM grids to the landscape features of interest. In this case, the regular 5 m DEM did not adequately capture the curvature known to exist in the landscape which appeared to require measurement over longer distances.

It is suggested that problems with low curvature might be reduced by producing gridded DEMs using analytical surfacing methods rather than the numerical methods most often used at present. Analytical methods preserve and enhance curvatures in the original point data. Alternately, it might be necessary to calculate curvature for an area larger than a single 3 by 3 window (e.g. a 5x5 or 7x7 window) (Blaszczynski, 1997. A similar effect might be achieved by passing a 3x3 or 5x5 filter over the original curvature data and extracting the maximum value from the window for each grid cell at the centre of the window.

3.2.3 *Effect of multiple scales of spatial variation in a landscape*

Another difficult problem related to the existence of multiple scales of spatial variation in the landscape and with interest in features that existed at more than one scale.

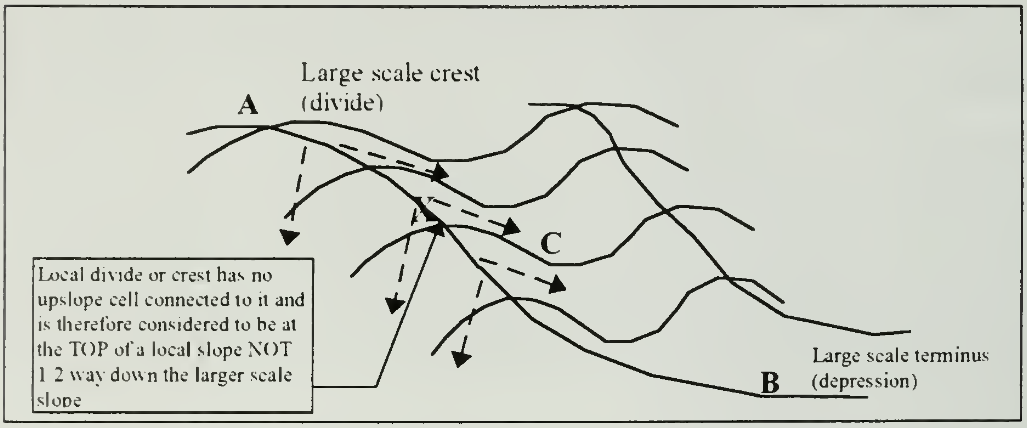


Figure 26. Illustration of the problem of landscape scale and relative landscape position

The best example of problems posed by multiple scales of spatial variation is provided by the challenge of establishing relative landscape position. Conceptually, relative landscape position is the position of a grid cell relative to a local crest and a local trough or stream channel. Relative landscape position can be measured in terms of linear distance from the cell to the nearest channel relative to linear distance between the nearest divide cell and the nearest channel cell (Skidmore, 1990). Alternatively, it may be computed in terms of the elevation of a cell above the elevation of the nearest channel cell relative to the difference in elevation between the nearest channel cell and nearest divide cell.

The problem arises in deciding how to define and locate the nearest divide cell and, less problematically, the nearest channel cell or base level cell. In the illustration (Figure 26) point X is clearly in a mid slope position as it would be judged to lie about half way between A and B In terms of both elevation and distance. Alternatively, one might view the landscape at a finer scale and judge point X to lie at the highest (or divide) point of a local ridge running laterally downslope from A to B. In this context, the nearest channel cell might be identified at C and X would be viewed as being 100% upslope relative to C and occupying a local crest landscape position.

The example demonstrates the difficulty of identifying features that exist at more than one scale. The problem is compounded by the algorithm used in the present exercise to compute flow paths and link cells hydrologically along flow paths. Many cells that clearly lie below other cells in middle to lower landscape positions are not connected by flow paths to any cells higher in the landscape. They are treated as local divide cells and are considered to be initial start cells for a new flow path. Since they are not connected to any upslope cells, it is very difficult to establish a hydrologically defined

topological linkage to what might logically be viewed as the nearest true upslope divide cell. All cells can be hydrologically linked to either a single downslope sink point or to the nearest defined channel cell, but the equivalent linkage to an upslope divide cell is not so easily achieved using flow based connectivity.

3.3 Potential applications of quantitative morphometric data

It is expected that quantitative morphometric data for type landscapes will find numerous applications. For example, scientists wishing to use digital soils databases to apply and evaluate numerical models such as WEPP or EPIC will require reliable quantitative input data, not just on soil characteristics, but also on landform attributes such as slope gradient, slope length and extent of off-site drainage (Wilson, 1996).

Data on slope gradient is frequently required for a wide variety of models (i.e. erosion, runoff) and decision rules (i.e. land capability, suitability for roads or septic fields). Current soils data bases generally provide only a qualitative assessment of from one to three slope classes thought to exercise control over the landscape. It is often not clear whether the slope class reported as dominant occupies the greatest extent of the landscape or whether it was simply judged to exert a dominant limiting influence for agricultural or other uses. Most soil maps and databases do not provide information on the relative extent of the landscape occupied by slope classes of minor extent. For many applications, the presence of extreme values of slope, even in minor amounts, may be of critical interest. For example, knowledge of the frequency distribution of all slope gradient classes in a landscape may reduce the current practice of selecting a single slope value (i.e. 7%) as characteristic of an entire landscape and then running a model (i.e. USLE) which computes a single result for the entire landscape that assumes the slope everywhere in the landscape is as stated (i.e. 7%). In this example, as much as 60-70% of the landscape may have slopes less than the stated 7% and the amount and extent of erosion would be grossly over estimated. This type of approach has tended to be widespread in the past. Future studies, aware of the component frequency distributions of slopes within a landscape, will be able to evaluate models (i.e. erosion as per USLE) for each component slope class or landform facet in the landscape (Wilson, 1996). This should produce more realistic and useful results representative of the sum of individual results (i.e. estimated erosion) for each different landform or slope component.

Data on the complete frequency distribution of slopes within a landscape may help to clarify current slope terminology such as dominant slope or limiting slope. Dominant and sub-dominant slope classes could be defined explicitly as the classes occupying the greatest and next greatest areal extent of a landscape. Limiting class could be defined as the steepest slope class present in the landscape in excess of a specified minimum extent (say 10%). Such definitions would introduce a level of consistency not currently present in soil maps and data bases.

Absolute slope aspect computed for type locations is unlikely to be widely useful as input to quantitative models and evaluations, however data on the relative frequency distribution of aspect for each type landscape is likely to be useful. It may help to quantify the existence of preferred orientations in certain landscapes (i.e. ridges, dunes) and the absence of preferred orientation in others (i.e. hummocky or undulating topography).

Knowledge of the frequency distribution of absolute relief in a landscape may help with assessment of processes that are affected by the potential energy of a landscape as controlled by elevation above a local base level (i.e. runoff, erosion, hillslope formation).

Knowledge of the frequency distribution of profile and plan curvatures may find application in studies of soil erosion and runoff as well. Areas that are convex in both plan and profile can be assumed to experience shedding and local surface runoff, while areas that are concave in plan can be expected to experience convergent, accelerating flow if convex in profile and convergent, decelerating or ponded flow if concave in profile. Such knowledge could help to quantify the proportions of landscapes most susceptible to erosion or flooding.

Many current algorithms and decision rules use estimates of total slope length from crest to toe slope or depression in combination with other data such as slope gradient to infer such things as runoff velocity or total erosive force. Slope length is considered to influence ease of cultivation and has been used as a criterion in assessing land suitability for agriculture. It has also been used as a criteria for classification of landforms (ECSS, 1987b). Quantitative data on the frequency distribution of total slope lengths within a landscape would improve current estimates (Wilson, 1996).

Upslope length is potentially useful for defining moisture relationships, however the current procedure does not establish hydrological linkages from all grid cells to their most logical nearest divide cell. Many cells are by-passed by flow paths computed using the steepest descent algorithm and are not connected to any upslope neighbors. This results in many isolated grid cells being treated as local divide cells, even when they are clearly located in mid to lower slope landscape positions. At present, the algorithm produces an estimate of the upslope length of the longest flow path which passes through each cell in a DEM. This can be equated to the kinetic energy or erosive force of channeled surface water flow passing over the cell. It does not provide a good indication of potential wetness as generated by near surface through flow. In contrast to surface flow, as computed by the steepest descent algorithm, near surface through flow is assumed to be able to move from each grid cell into all downslope neighbors with the amount of flow being a function of the steepness of the gradient between a cell and each of its down slope neighbors (Quinn et al., 1991, 1995). In this approach, any cell in a gridded DEM that lies below and adjacent to another cell, will receive at least some flow from the overlying neighbor. It may be necessary to modify

the current algorithm to compute the diffuse upslope contributing area (Quinn et al., 1991; 1995) or to compute the linear distance to a true upslope divide cell.

A valid and useful measure of downslope length is currently computed for every cell in a gridded DEM. This derivative measures the linear distance downslope from a grid cell to the cell where overland flow is considered to terminate, usually a depression centre cell. It may be considered as the dispersal distance from a cell to its flow terminus. Knowledge of the frequency distribution of downslope length may find application in such areas as estimating the potential of a landscape to deliver non-point source pollutants (i.e. herbicides, pesticides, fertilizers) to ponds or drainage ways by means of surface flow. The greater the distance a cell is from a terminus, the less likely it may be to deliver its load to a down slope terminus.

Quantitative data on landscape position, measured in terms of relative relief, is likely to prove most useful for establishing landscape context as an aid to landform segmentation. Knowledge of the frequency distribution of relative relief may also prove useful for interpreting the potential energy of a landscape for such processes as runoff and erosion. Frequency distributions may be interpreted to infer some aspects of the shape of a landscape. For example, if a landscape has a significant majority of its area (say 70%) lying below the 50% point of relative relief (i.e. midslope) it may be assumed to be dominated by long, low relief toe slopes and will likely exhibit short and steep midslopes.

Quantitative data on the frequency distribution of watersheds, their size and degree of off-site drainage have the potential to improve interpretations of the degree to which landscapes might contribute runoff and concomitant, water borne non-point source pollution (i.e. sediments, agricultural chemicals) to adjacent landscapes or drainage channels. Conversely it might be desirable to estimate the degree to which landscapes will retain runoff, sediments or pollution.

Wilson (1996) provides a thoughtful review of the potential for using DEM data to supply many of the terrain based attributes required as input for a number of widely used distributed, erosion and non-point source pollution models. He identifies a number of problems with using DEM data for model input and for linking models to commercial geographic information systems (GIS). He notes that "the paucity of input data at the preferred spatial resolution and difficulty in handling multiple inputs that vary in different ways across the landscape (i.e. the modifiable area problem) have emerged as major impediments to the successful application of models in environmental management" (Wilson, 1996).

It is the intention of this bulletin to propose the calculation and provision of quantitative morphometric data for type landscapes attached to soil survey map units. Such data would provide an invaluable first approximation of the quantitative distribution of values for a variety of important terrain attributes required as input for deterministic models or heuristic decision support systems.

Where available, high resolution site specific DEM data could, and should, be substituted for the generalized data computed for type landscapes. In the absence of site specific DEM data however, a proposed database of morphometric data for type landscapes as identified in soil survey map units could greatly extend the utility of current and emerging digital soils databases.

Numerous examples exist of isolated studies or individual projects that have computed terrain attributes from digital elevation data and successfully utilized the quantitative data as input to process models (Wilson, 1996) or to characterize or analyze specific landforms in terms of hydrological or soil forming processes (Pennock and De Jong., 1987; Zebarth and De Jong, 1989a,b; Pennock et al., 1987, 1994; Mulla, 1986; Lanyon and Hall, 1983a,b; Gessler et al., 1996). What has not yet occurred, and what this bulletin hopes to promote, is routine incorporation of quantitatively derived morphometric data into standard soil survey digital databases designed for widespread distribution and use. The mere incorporation of such data into digital soils databases would do much to foster awareness of the variation in terrain attributes within commonly recognized landforms and to promote adoption and use of continuously varying quantitative landform data in place of current qualitative data expressed as single values, or at best as estimated ranges for type landforms.

4. AUTOMATED LANDFORM SEGMENTATION

Automated procedures for producing illustrations of soil-landscape relationships require an ability to define the location and extent of various landform segments or land facets within each landscape. These land facets should correspond to the commonly used concepts of surface form and landform position embodied in such terms as crest, upper slope, mid slope, lower or toe slope and depression. These are the landform elements most commonly used by existing manual procedures for describing and illustrating the distribution of soils within landscapes. It is desirable that procedures for defining landform elements be as systematic and as replicable as possible. It is envisaged that they should be applied automatically to data extracted from digital elevation models (DEMs).

The landscape morphology derivatives described in section 3 were all evaluated to assess their utility for segmenting landforms into components or facets (data not presented). Slope gradient, curvature and relative relief were ultimately determined to offer the greatest potential for effective landform segmentation.

Four models were investigated. The first was a seven unit model based on curvature and gradient described by Pennock, Zebarth and de Jong (1987). The second was a four unit model that considered only relative slope position in allocating each grid cell to one of four possible landscape facets (Crest, Upper Slope, Lower Slope, Depression). The third was an eight unit model that used slope gradient, in addition to relative slope position, to assign each cell to one of 8 terrain facets (Level Interfluve, Sloping Shoulder or Crest, Level Upper Slope or Terrace, Steep Upper Slope, Steep Lower Slope, Level Lower Slope, Sloping Depression Rim and Level Depression).

4.1 Potential models for landform segmentation

4.1.1 Landform segmentation according to Pennock et al.

The landform classification system of Pennock et al. (1987) was selected as a starting point for the current exercise (Table 2). Their seven unit model uses downslope (profile) curvature as the primary classification criteria, with the assumption that shoulders are convex, footslopes concave and backslopes linear in form. A value for profile curvature of +/- 0.1 deg/m is used to distinguish convex or concave elements from planar elements. These three basic landscape entities are further subdivided according to whether they are convex (divergent) or concave (convergent) in plan. Linear units with slope gradients less than 3 degrees are further separated from the more strongly sloping convergent and divergent backslopes. At the time the research was conducted, the authors were not aware of, and did not incorporate, more recent improvements to the original 7 unit Pennock model (Pennock, Anderson and deJong, 1994).

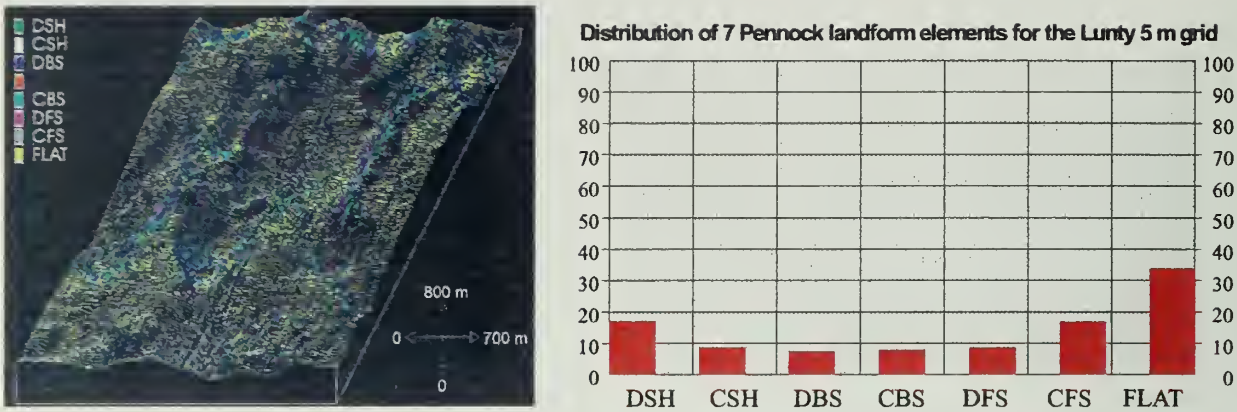


Figure 27. 3D illustration of the Pennock et al. (1987) classification applied to the 5 m by 5 m DEM

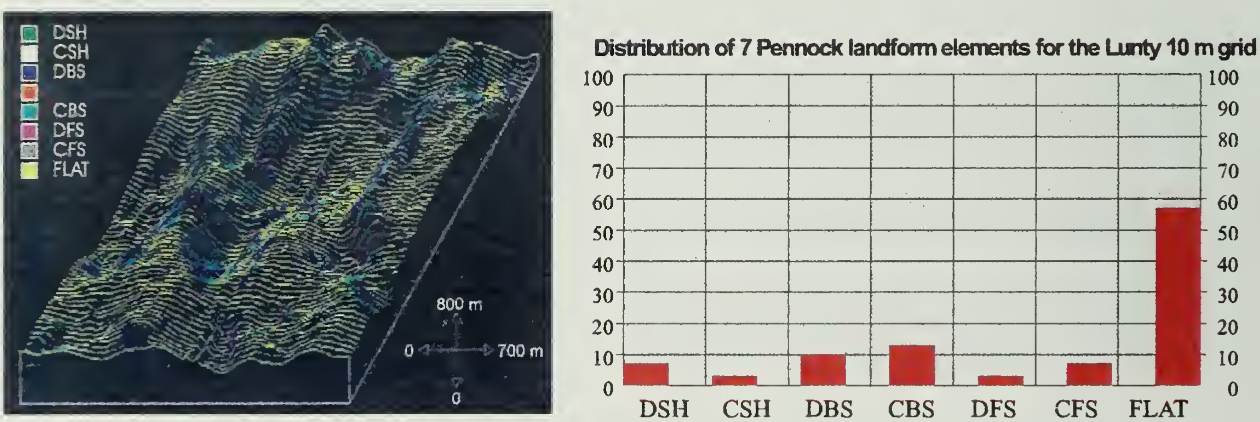


Figure 28. 3D illustration of the Pennock et al. (1987) classification applied to the 10 m by 10 m DEM

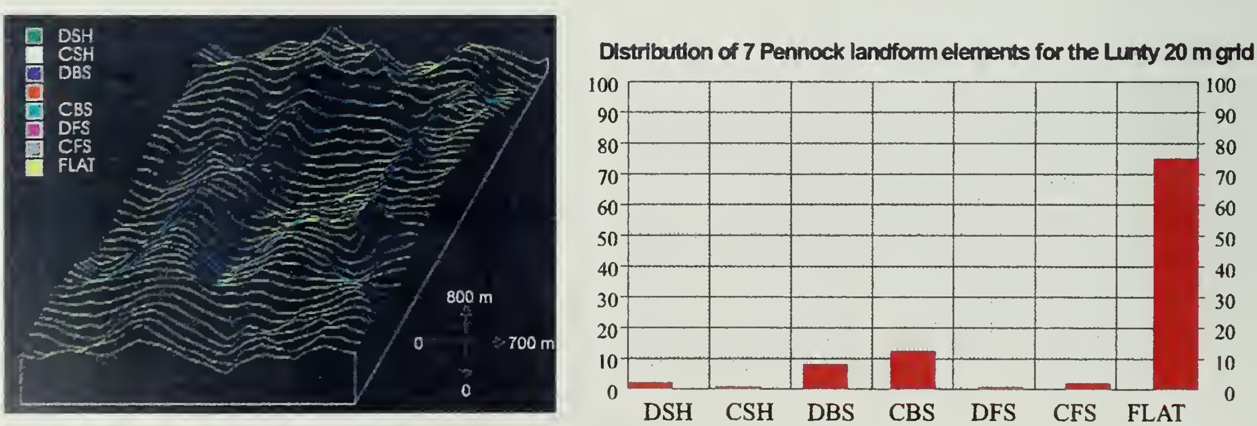


Figure 29. 3D illustration of the Pennock et al. (1987) classification applied to the 20 m by 20 m DEM

Table 2. Classification criteria for landform elements (Pennock et al., 1987)

No.	Landform Element Name	Symbol.	Profile Curvature (deg/m)	Plan Curvature (deg/m)	Slope Gradient (deg)
1	Divergent Shoulder	DSH	> 0.10	> 0.0	NA
2	Convergent Shoulder	CSR	> 0.10	< 0.0	NA
3	Divergent Back Slope	DBS	-0.10 to +0.10	> 0.0	> 3 deg
4	Convergent Back Slope	CBS	-0.10 to +0.10	< 0.0	> 3 deg
5	Divergent Foot Slope	DFS	< 0.10	> 0.0	NA
6	Convergent Foot Slope	CFS	< 0.10	< 0.0	NA
7	Linear	L	-0.10 to +0.10	NA	< 3 deg

An initial application of the above classification rules of Pennock et al. (1987) to derivatives computed for the test site 5m by 5 m DEM was not successful (data not shown). Almost all grid cells were classified as linear so there was no effective differentiation of the test landscape The reason most cells were classed as linear is that fully 90% of the cells in the test DEM had slopes less than 5% (Figure 5) and 60% of all cells had profile curvatures between -0.1 and +0.1 deg/m (Figure 11). The 5% (3 degree) slope limit imposed by the rules of Pennock et al. (1987) would mean that a very large proportion of prairie landscapes would be classified into low gradient linear landform elements. This would not address the objectives of the present project, which require automated segmentation of a large number of landscapes with relatively low relief and low slope gradients.

The original classification rules of Pennock et al. (1987) were therefore revised to reflect the preponderance of slopes of low gradient. A new limit of 2% was selected to separate low gradient linear landform elements from higher gradient linear elements. The remaining classification criteria were retained as per Table 2. Application of the revised classification rules still failed to produce a spatially coherent landform segmentation (Figure 27). It was thought that this problem might be related to ineffective capture of profile curvature by the 5 m grid spacing of the test DEM. Consequently, the test data set was resampled to produce more generalized DEMs with grid cell spacings of 10 m, 20 m and 50 m. The three terrain derivatives required for implementing the rules of Pennock et al. (1987) were computed for each of the new DEMs and the rules were applied to define the 7 landform elements (Figures 28 & 29).

Fragmentation was not eliminated, but it was markedly reduced for the 10 m by 10 m DEM (Figure 28). The resulting spatial entities were larger, more coherent and more generalized than for the 5 m by 5m DEM. However they were not considered generalized enough to define simple landform element models for portraying the relative distribution of soils at a few critical landscape positions. One major concern was the large extent of the landscape classified as low gradient linear landscape elements. This class did not differentiate between low gradient areas in low-lying

landscape positions and low gradient elements in upper landscape positions. Furthermore, the relative extent of the landscape placed into this class increased significantly for the 10 m by 10 m DEM compared to the 5 m by 5 m DEM due to generalization of slope gradient calculations for the landscape arising from using a larger DEM grid interval.

The landform element classification produced for the 20 m by 20 m DEM (Figure 29) had an even greater proportion of low gradient planar elements. It did not differentiate the landscape into the number and kind of landform elements required for illustrating soil-landscape relationships at the scale of interest.

4.1.2 A simple four class segmentation based on relative relief

Several alternative approaches were explored in an attempt to define larger, more coherent, more generalized landform elements more suitable for illustrating conceptual models of soil-landform relationships. These attempted to capture the missing element in the approach of Pennock et al. (1987), namely some explicit measure of relative landscape position or landscape context. Evaluation of the previously computed measures of relative slope position revealed relative relief to provide the most effective overall measure of landscape context. It was possible to produce a very simple, but very effective, segmentation of the landscape into four relative landscape positions (crest to shoulder, upper to mid slope, mid to lower slope and lower slope to depression) by grouping grid cells according to four classes of relative relief (Table 3 & Figure 30).

Table 3. Classification rules for the simple four unit landform element model

No.	Name	Relative Relief
1	Crest - Shoulder	> 70%
2	Upper - Mid Slope	40-70%
3	Mid - Lower Slope	20-40%
4	Toe - Depression	< 20%

Simplicity and spatial coherence are the principal advantages of landform segmentation based solely on relative relief (Figure 30). Relative relief removes the effects of short distance, high frequency variation in the DEM data set. Conversion of absolute relief to dimensionless units (%) of relative relief further removes scale influences arising from differences in the absolute size of different hillslopes and watersheds. The resulting classification produces large, contiguous areas that reflect simple conceptual notions of relative landform position. The progression from crest to upper slope to mid slope to depression is systematic, continuous and clearly defined (Figure 30). The class limits (Table 3) are purely arbitrary and would likely require adjustment for different types of landscapes. A practical modification might compute the statistical frequency of shoulders, backslopes and footslopes according to the criteria of Pennock et al. (1987) and then select class limits for the relative relief data for each type landscape that resulted in definition of an equivalent frequency of each of these landscape elements.

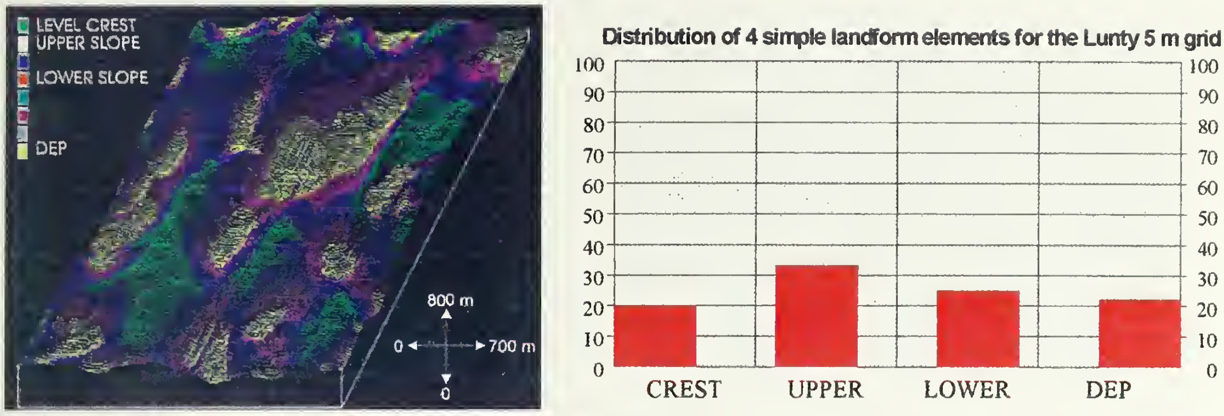


Figure 30. 3D Illustration and frequency distribution for the simple 4 class landform element model

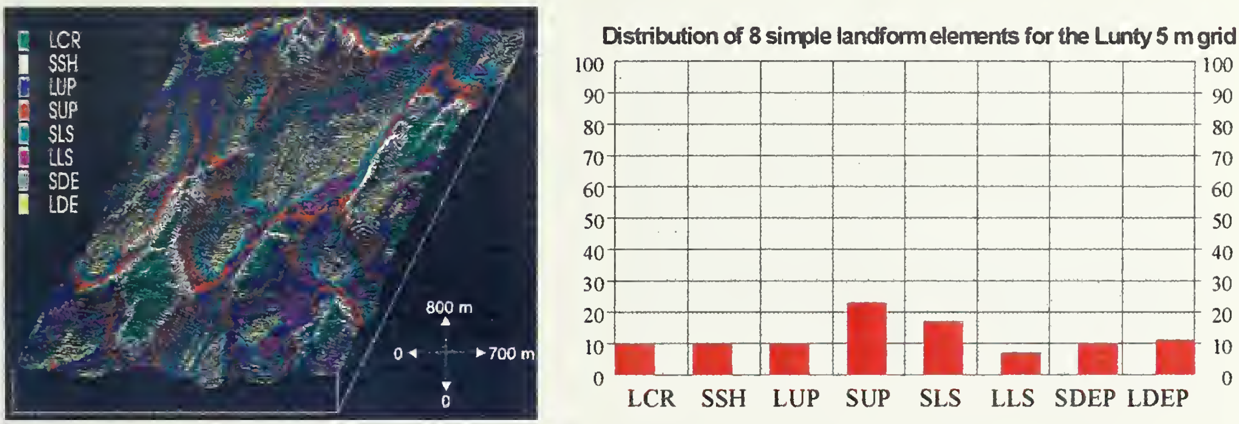


Figure 31. 3D illustration and frequency distribution for the 8 class landform element model

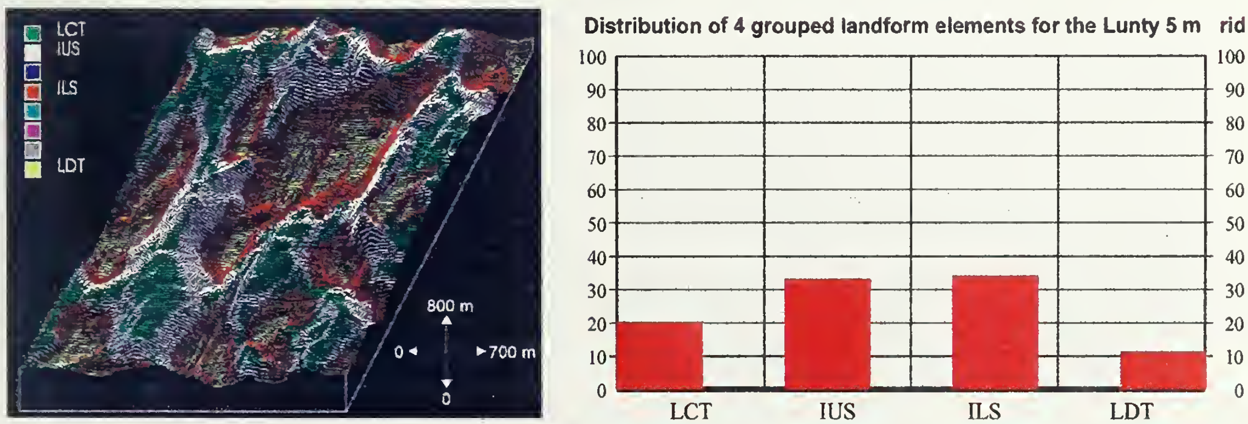


Figure 32. 3D illustration and frequency distribution for the 8 class model reduced to 4 classes

4.1.3 An 8 class segmentation based on slope & relative relief

One concern with the simple four class segmentation was that each of the four landform position classes exhibited a wide variety of slope gradients. Planar elements were grouped into the same class as more strongly sloping elements. The rule base for the four unit model was therefore extended to further subdivide each of the four initial classes according to slope gradient using a break point for slope gradient of 2% (Table 4).

Application of the classification rules (Table 4) to the test DEM produced a more meaningful, but more complex classification (Figure 31). The 3D view clearly illustrates such improvements as differentiation of level to nearly level interfluves (dark green) from more strongly sloping shoulders (white). Areas classified as nearly level upper slopes (dark blue) appear to represent local crests and divides in relatively lower landscape positions, while areas classified as higher gradient upper slopes (bright red) more closely approximate the conceptual understanding of mid to upper slopes. The distinction between more strongly sloping mid to lower slopes (bright green) and nearly level foot slopes or toe slopes (magenta) appears to be less effective, as does the distinction between sloping depressions (light gray) and level depressions (yellow). For this particular data set, classes 5, 6 and 7 could conceivably be merged.

Table 4. Classification rules for the eight unit landform element model

No.	Name	Symbol	Relative Relief	Slope Gradient
1	Level Crest	LCR	> 70%	< 2%
2	Sloping Shoulder	SSH	> 70%	> 2%
3	Level Upper Slope	LUP	40-70%	< 2%
4	Sloping Upper Slope	SUP	40-70%	> 2%
5	Sloping Lower Slope	SLS	20-40%	> 2%
6	Level Lower Slope	LLS	20-40%	< 2%
7	Sloping Depression	SDE	< 20%	> 2%
8	Level Depression	LDE	< 20%	< 2%

4.1.4 Generalization of the 8 unit model into 4 groups

The 8 unit classification was simplified by joining classes 1 with 3, 2 with 4, 5 with 6 and 7 and retaining class 8 (Figure 32). This produced a different 4 unit classification (Table 5) consisting of nearly level crests, interfluves and upslope terraces (dark green), somewhat sloping (>2%) crests to mid slopes (white), somewhat sloping (>2%) mid to lower slopes (dark red) and nearly level depressions (bright yellow). These four classes each exhibited a unique and limited range of slope gradient and relative landscape position. Visual analysis supported the notion that each landform element also exhibited a dominant surface shape consistent with the notion that upper slopes

are convex in profile and lower slopes are concave. The new classification combined the simplicity of the initial four unit model with the more tightly defined geomorphic attributes of the eight unit model..

Table 5. Classification rules for generalizing the 8 unit model into 4 units

No.	Name	Symbol	Slope Gradient	Relative Relief
1	Level Crests & Terraces	LCT	< 2%	> 40%
2	Inclined Upper Slopes	IUS	> 2%	> 40%
3	Inclined Mid to Lower Slopes	ILS	> 2%	< 40%
4	Level Depressions & Lower Terraces	LDT	< 2%	< 20%

4.2 Evaluation of the landform segmentation models

Two main problems were evident with the classification of Pennock et al. (1987). The first was poor spatial coherence of the pattern of landform elements. Their system is based on the assumption that local surface form is an accurate indicator of relative landscape position. This may be true in a statistical sense, but high frequency variation in local surface form picked up by high resolution DEMs makes it very unlikely that a large number of contiguous grid cells will all exhibit a similar local surface form. This leads to a fragmented spatial pattern of classified landform elements which is not general enough to use for simple illustrations of soil-landscape conceptual models. Pennock et al (1994) recognized and offered a solution to this problem of spatial fragmentation.

The second concern was that the Pennock model was unable to distinguish whether low gradient planar elements were located in upper or lower landform positions. This was a critical shortcoming from the point of view of the intended application. While planar elements might have a similar external shape in both landform positions, relative landform position exercises considerable influence on the kinds and nature of soils. Since the desired application of the classified DEMs was to illustrate the conceptual pattern of distribution of soils in different landform positions, it was essential that any classification be able to distinguish between upland and low-lying relative landform positions. Pennock et al. (1994) recognized this limitation in their original 7 unit model and proposed using upslope catchment area to differentiate level landscapes in upper slope locations from those in lower slope to depressional locations.

The principal limitation of the initial, simple four unit model is minor misclassification and confusion. The model performed well in defining depressions and lower slopes. It was, however, susceptible to mis-classifying local crests and shoulders in low-lying landscape positions as midslopes. Several examples of misclassification were evident in Figure 30. In this case, these misclassed areas were, in fact, more like midslopes in terms of their composition of soils. This was because the distribution of solonetzic soils

in the test landscape is highly dependent upon height above the local water table, which is strongly correlated with relative relief.

A second limitation of the simple four unit classification is that it is not based on local shape or slope gradient so cannot ensure that each landform element (crest, midslope, lower slope, depression) has a characteristic shape or gradient. The logic inherent in the four unit approach is, in fact, the inverse of that inherent in the approach of Pennock et al., (1987). Pennock's approach assumes the existence of a direct, one to one, relationship between local surface form (i.e. convex-concave) and relative landscape position, with surface form being used to predict landscape position. Since the four unit model computed relative slope position directly, it adopted the inverse assumption that grid cells within each slope position class will mainly exhibit surface forms characteristic of that landscape position.

The main benefit of the 8 unit classification appeared to come from differentiation of sloping shoulders (class 2) from nearly level crests and interfluves (classes 1 & 3). The main concern with the 8 unit model was that the number of landform elements was too large to support convenient assignment of soils to landform elements. The current level of tacit knowledge pertaining to soil-landscape relationships would likely be challenged to allocate soils to just 4 or 5 relative landform positions. A simpler model was required.

The eight unit model (Figure 31) was very effective at producing large, recognizable landform segments that were correctly labeled as to their relative position in the landscape and their dominant slope and shape characteristics. Eight units was, however, judged to be more than required for illustrative purposes and several of the units were deemed to be relatively similar. The eight unit model was therefore generalized by combining elements with similar characteristics to form a simplified combined four unit model (Figure 32).

Some difficulty was encountered in deciding whether to group level lower slopes and sloping depressions from the 8 unit model with depressions or with lower slopes in the reduced four unit model. In the case of the test DEM, it appeared that both level lower slopes and sloping depressions were best grouped with sloping lower slopes. This grouping may have to be reconsidered for other landforms. It might be advisable to consider splitting the upper and lower slope landform elements into three landform elements, namely upper, mid and lower. This would create a five unit model that would conform more closely to the widely accepted differentiation of shoulders (upper), backslopes (mid) and footslopes (lower) inherent in the classification of Pennock et al. (1987).

The simplified 4 unit model was judged to provide the best combination of simplicity of interpretation and accuracy of landform position identification. It was adopted in preference to the 8 unit model because insufficient tacit knowledge was available to permit reliable assignment of soils to the larger number of facets in the 8 unit model.

4.2.1 *Distribution of soils in relation to the combined 4 unit model*

The simplified, combined four unit model segments the landscape into units that can be readily interpreted in terms of the known distribution of soils (see Appendix 1). The level crests and upper terraces are associated predominantly with well drained chernozemic soils (EOR) with minor inclusions of other weakly saline to weakly solonetzic soils. The inclined upper slopes are dominated by the weakly saline to weakly solonetzic soils (DYD, HER) with inclusions of well drained non-saline chernozems (EOR). The inclined lower slopes are characterized by a complex mixture of strongly developed Solodized Solonetz (KLM) and a variety of other soils that range from slightly to strongly saline and solonetzic (DYD, FMN). Both upland and low-lying depressions are dominated by Humic Luvic Gleysols (COR) with some Orthic Humic Gleysols (HGT) in the centers of larger, more permanent depressions.

The four unit model performed well in all situations except for portraying the spatial distribution of Solonetzic Gleysols (FMN). These soils are most commonly associated with sloping depressions (unit 7 in the 8 unit model). Combining unit 7 into the lower slope unit of the simplified four unit model means that the simplified four unit model is unable to depict the location of Solonetzic Gleysols as precisely as might be possible.

4.2.2 *Simplicity and interpretability of the combined 4 unit model*

The combined four unit model (Figure 32) presents a very simplified, almost cartoon-like, representation of the landscape. This has both advantages and limitations in terms of interpretation and use.

The 4 unit model's simplicity is its principal advantage. It defines large, coherent areas that are clearly differentiated according to relative position in the landscape (i.e. upslope or downslope). In addition, each of the units has, by definition, a restricted range of slope gradients (level versus steeper). Each of the units also has, by inference, a relatively characteristic range of other morphological attributes, including down-slope curvature, up-slope and down-slope length. It would be possible to cross reference the four unit classification image against the raster data sets for individual morphological attributes (i.e. curvature) to verify and quantify these limited ranges for each unit. The 4 unit model conforms quite closely to the simple conceptual models of soil-landscape relationships commonly used by soil scientists to assist in mapping and explaining the topographical distribution of soils with landscapes.

One of the primary limitations of the combined 4 unit model is that it does not incorporate recognition of across-slope curvature in the landscape. All upper slopes are considered equivalent, even though it is well known that concave areas of convergent flow in upper landscapes can have considerably different assemblages of soils than convex areas of divergent flow. This is also true of convergent and divergent lower slopes, though to a lesser degree. The 4 unit model adopts a simplified, almost two dimensional, view of the landscape and applies it in three dimensions. It would

undoubtedly be more correct to adopt a true three dimensional view that incorporated across-slope curvature. The result, however, would be a model that was more complex than could be interpreted given current levels of knowledge regarding known patterns of distribution of soils in the landscape.

4.3 Potential applications of the landform segmentation data

Automated landform segmentation provides the basic elements for simple, but meaningful three dimensional images for visual display and manual interpretation of soil-landscape relationships.

The advent of computer programs for producing realistic 3D visualizations of terrain and the increasing availability of digital elevation data of a suitable resolution afford possibilities for replacing current manual procedures with automating routines for creating 3D illustrations of soil-landscape relationships. Tabular information produced by automated landform segmentation can then be used to generate 3D illustrations of soil-landscape models automatically.

The landform segmentation data should prove useful for quantitative application of detailed, site level, simulation models to extensive areas characterized by particular soil-landscape associations. In such cases, it may be necessary to compute and report quantitative statistics for each landform element for such morphological attributes as slope gradient, slope length and curvature. This could be accomplished by cross-tabulating the 4 unit classification data against the morphological data.

Landform segmentation can also provide the basic management units to support precision farming by providing a spatial context for assigning soil characteristics to landform elements.

5. ALLOCATION OF SOILS TO LANDFORM ELEMENTS

5.1 Introduction

Users of current soil survey reports and maps have grown accustomed to consulting simple schematic diagrams that illustrate the general shape of each of the major soil-landscape units in a given area and portray the general pattern of distribution within the landscape of the various soils included in each unit.

The existing manual procedures for producing these diagrams require soil analysts to possess and apply considerable background, or tacit, knowledge regarding the most likely location(s) in the landscape for each named soil. This knowledge is most often based on extensive practical experience gained through observation and recording of relationships between soils and landform position during local field mapping. Analysts use this acquired tacit knowledge to make judgments and statements about which soils are most likely to be found in each of several idealized landform elements. To date, most schematic diagrams have been constructed as simple two dimensional cross sections. Most such cross sections have limited the portrayal of soil-landscape relationships to a general association of soils with upper, mid, lower or depressional landform positions.

The current inability of the soils data bases to explicitly describe relationships between mapped soils and landform position offers several challenges and opportunities. One challenge is to find an efficient way to capture and apply the tacit knowledge required to assign soils to their most likely landform positions. This assignment or allocation must be accomplished in order to generate schematic illustrations of soil-landscape relationships without recourse to direct input by soil analysts. Given the large number of potential soil-landscape models, it is virtually imperative that the procedures for allocating soils to landform position be systematic and automated.

Automatic generation of diagrams illustrating the relative distribution of soils in landscapes required a mechanism to automatically allocate soils to each of the defined landform positions in a manner that reflected generally accepted tacit regional knowledge regarding the relative distribution of soils with respect to landform position. It was considered that any automated procedure for allocating soils to relative landscape position had to be able to use existing data about the soils stored in existing digital data bases (e.g. National Soil Data Base). It also had to be able to capture and use existing tacit knowledge about soil-landscape relationships rather than requiring identification or creation of quantitative data sets and decision rules. Finally, it had to be flexible enough that the basic approach could be easily adapted to generate and apply new regional rule bases in different ecological areas. This precluded approaches based on construction of elaborate Boolean decision rules specific to a given area.

5.2 Creation of a tacit knowledge rule base

Allocation of soils to landform facets was accomplished using an expert system approach based on possibility analysis (a variant of fuzzy logic) applied to readily available data for each soil. All required data were extracted automatically from the NSDB soil names file (SNF).

A limited number of soil attributes which were known be correlated to landform position were included in the rule base. Attributes selected for initial development and testing of the rule base (Table 6) were Sub-Group classification, drainage class, salinity class and soil variant.

Table 6. Soil attributes selected for inclusion in a rule base of tacit knowledge

Soil Attribute	Assumed Relationship of Soil Attribute to Relative Landform Position
SubGroup	It is assumed that some, but not all, soil SubGroups can be related to landform position, especially gleyed SubGroups (lower), various Solonetzic SubGroups (mid to lower), Eluviated SubGroups (mid to lower) and Calcareous or Rego SubGroups (crest to upper)
Drainage Class	It is assumed that, in general, there is a progressive relationship from rapidly to well drained in upper landform positions to imperfectly to poorly drained in lower landform positions.
Salinity Class	It is assumed that saline soils are more likely to occur in mid slope to depressional landscape positions.
Soil Variant	A number of soil variants provide clues as to likely landscape position. For example, an eroded variant is considered more likely to occur on a crest or shoulder as is a stony variant, whereas a thick variant is more likely to occur in a lower or toe slope.
PM Type	This was not used as an attribute for allocating soils to landform position. In cases where all other attributes produce a similar estimate of likely landform position it may be possible to suggest that lacustrine or fluvial soils occupy lower landform positions than, for example, till parent materials.
PM Texture	As with PM type, PM texture was not used as a primary criteria. In certain ambiguous cases were the primary criteria fail to allocate soils to landform positions it may be possible to suggest that, for example, coarser soils are more likely to occur in upper to crest landform positions, and finer textured soils in lower landform positions

Table 7. Relative likelihood of soil drainage class occurring in each landform position

Code	Description	Level Crests & Terrace (LCT)	Inclined Upper Slopes (IUS)	Inclined Lower Slopes (ILS)	Level Depressions & Lower Terraces (LDT)
-	Not Applicable	100	100	100	100
VR	Very Rapidly	95	100	35	1
R	Rapidly	80	85	40	5
W	Well	85	80	50	10
MW	Moderately Well	70	60	90	40
I	Imperfectly	30	10	80	75
P	Poorly	10	5	60	95
VP	Very Poorly	5	1	45	100

Each attribute was interpreted in terms of its relative likelihood of occurring in each of the four defined landform positions. The relative likelihood tables capture local tacit knowledge regarding the principal environmental factors that affect the distribution of soils in the landscape in a particular ecological setting.

For example, drainage class is considered to be strongly related to landscape position. Well and rapidly drained soils were considered much more likely to be located in crests and upper slopes than in depressions (Table 7). Conversely, poorly drained soils are considered most likely to occur in depressions and imperfectly drained soils most likely to occur in lower to toe slopes. A similar logic was applied to develop relative likelihood tables for each of the other soil attributes listed in Table 6. The local rule base of tacit knowledge was effectively complete once agreement was achieved on the relative likelihood values to assign to each of the soil attributes for each of the defined landform elements. The rule base can then be applied to any soil or combination of soils of interest.

5.3 Application of the rule base

The general practice, in soil survey, is to identify a limited number of soils that are considered to best describe any area (polygon) of interest. This typically ranges from 3 (e.g. NSDB) to 5 (CAESA-SIP, Saskatchewan) or more soils.

The usual situation is to be presented with a list of 3 to 5 soils and a single code for type landscape. The challenge is to decide which location(s) in the landscape each of the listed soils is most likely to occupy. Two steps are involved.

1. In step 1, each of the listed soils is evaluated in terms of its overall relative likelihood of occurring in each of the 4 defined landform elements. The overall likelihood is computed for each soil and each landform element as an arithmetic mean of the individual relative likelihood values for each of four soil attributes (Table 9). For any given combination of soils, the result is an assessment of the relative likelihood that each soil will occupy any given landform element (Table 10).
2. The second step involves comparing the relative likelihood of each of the soils occurring in each of the landform elements in order to assign the most likely soil to each landform element. This step requires the following information:
    a) The proportion of the landscape occupied by each of the (4) defined landform elements
    b) The proportion of the landscape occupied by each of the listed soils
    c) The overall relative likelihood of occurrence in each landform element for each of the listed soils

If ***n*** soils are listed as occurring in a given polygon on a given landscape, the program systematically considers the relative likelihood of each soil occurring in each landform

position to assign soils to landform facets. Each facet is considered in a specific sequence such that extremes are considered first. First soils are allocated to level upper elements (LCT) then to level lower to depressional elements (LDT) followed by inclined upper slopes (IUS) and then finally inclined lower slopes (ILS).

At each stage, the soil considered most likely to inhabit a facet is assigned to that facet until the areal extent of the facet (e.g. 20%) is matched by the areal extent of the soils that have been assigned to it (e.g. 20%). The next facet in the sequence is then considered and the most likely soils allocated to it and so on, until all facets have been considered and all soils allocated.

5.3.1 An example application of the rule base

The relative extents and defining characteristics of the five main soils identified at the Lunty site are listed in Table 8. Each of these individual characteristics was converted into a relative likelihood of occurring on a level crest or terrace (LCT) for each of the five soils (Table 9). Similar look-up tables (not shown) were created for the other three defined landform facets. A program was written that looked up all characteristics for each soil in the NSDB soil names file (SNF) then consulted the relative likelihood tables to determine the appropriate likelihood value for each individual characteristic for each combination of soil and landform position.

A single value for the overall likelihood of each soil occurring in each landform facet was computed as the mean of four individual values (Table 9). The result (Table 10) ranks each soil in terms of its likelihood of occurring in each landform facet.

The allocation (Table 11) was achieved by considering the facets in the sequence LCT, LDT, IUS, ILS. In each step, the soil deemed most likely to occupy a facet was assigned to the facet until all of the available extent of soil was assigned or all of the available extent of the facet was allocated one or more soils. If the known extent of the facet was not completely occupied by the soil deemed most likely to occupy if, then the next most likely soil was allocated, until either all of the available extent of that soil was allocated or all of the available extent of the facet was filled. Once all of the extent of the first facet (LCT) was assigned soils, the next facet (LDT) was considered in the same fashion.

The final allocation of soils to landform facets (Table 11) is consistent with the known distribution of soils in the landscape. Well drained soils (EOR) occupy crests and upper terraces. Upper slopes are occupied by both EOR soils and moderately well drained, weakly solonetzic soils (DYD). Mid to lower slopes are occupied by a complex mixture of weakly (DYD) to strongly solonetzic (KLM) soils and Solonetzic Gleysols (FMN). The depressions are dominated by poorly drained Humic Luvic Gleysols (COR) but have rings of Solonetzic Gleysols (FMN) around their rims.

Table 8. Extent and characteristics of the five main soils at the example site

Soil Code	Soil Name	Percent Extent	SubGroup	Drainage	Salinity	Variant	PM Type	PM Texture
EOR	Elnora	30	O.BL	W	NS	NA	TILL	MF
DYD	Daysland	30	BL.SO	W	WS	NA	TILL	MF
KLM	Killam	15	BL.SS	MW	MS	NA	TILL	MF
FMN	Foreman	10	SZ.HG	P	MS	FI	LACU	FI
COR	Cordel	15	HU.LG	P	NS	FI	LACU	FI

Table 9. Relative likelihood of individual characteristics occurring on a level crest or terrace

Soil Code	Soil Name	Mean Likelihood	SubGroup	Drainage	Salinity	Variant
EOR	Elnora	91	100	85	80	100
DYD	Daysland	81	80	85	60	100
KLM	Killam	65	50	70	40	100
FMN	Foreman	20	10	10	40	20
COR	Cordel	29	5	10	80	20

Table 10. Relative likelihood values for each example soil for each landform element

Soil Code	Description	Level Crest or Terrace (LCT)	Inclined Upper Slopes (IUS)	Inclined Lower Slopes (ILS)	Level Depressions & Lower Terraces (LDT)
EOR	Orthic Black	91	90	63	55
DYD	Black Solod	81	73	68	50
KLM	Black Solodized Solonetz	65	60	90	68
FMN	Solonetzic Gleysol	20	15	80	96
COR	Humic Luvic Gleysol	29	34	70	99

Table 11. Percent extent of the five example soils in each of the four landform facets

Soil Code	Percent Extent in Landscape	Level Crest or Terrace (LCT)	Inclined Upper Slopes (IUS)	Inclined Lower Slopes (ILS)	Level Depressions & Lower Terraces (LDT)
	% of Landscape	20	33	35	12
EOR	30	20	10		
DYD	30		23	7	
KLM	15			15	
FMN	15			13	2
COR	10				10

5.4 Analysis and evaluation of the allocation procedures

The automatic allocation procedures produced a reasonable and useful assignment of soils to landform position for the example soils and landscape.

Two aspects of the described procedures stand out. The first is the concept of defining a relative likelihood of occurring in a given landform position for each soil and landform position based on consideration of known relationships between selected fundamental soil attributes and landform position. The second is the concept of assigning soils to relative landform position based on conditional or contextual evaluations of unanticipated combinations of soils and landscapes.

5.4.1 The concept of a rule base founded on relative likelihood

The concept of assigning each soil a relative likelihood of occurring in each of a limited number of defined landform positions is both intuitive and logical. It mirrors inherent, mainly undocumented, thought processes adopted by many experienced soil mappers in developing and applying conceptual models to assist in the production of soil maps. It has been common practice, in existing soil survey reports, to provide some indication of the relative landform position or positions in which a particular mapped soil is most likely to be found. The described procedures simply formalize and extend this practice.

Similarly, most experienced soil mappers generalize their field observations during the course of local mapping projects. They develop conceptual models to relate individual soil attributes such as drainage class, parent material type and texture, Subgroup classification and salinity or calcareousness to the portions of the landscape where they are most likely to occur. These undocumented generalizations become the basis for constructing descriptions of specific soil-landscape models. Again, the procedures described here simply formalize and extend methods that are in common usage but which are usually undocumented.

There is likely to be initial disagreement among local soils experts regarding which soil attributes warrant inclusion in a given rule base and on the specific values that should be assigned for relative likelihood for each class or value of each attribute in each landform position. This is not considered to be a problem. Rather, it represents an opportunity to engage local experts in a formal systematic process for capturing and codifying their local knowledge.

Interactive discussions among groups of local experts could lead to emergence of a consensus on which attributes could be relied upon to display a consistent and predictable relationship to landform position and should therefore be included in the rule base. Similarly, achievement of consensus on the specific relative likelihood values to assign to each attribute for each landform facet should result in a credible and effective rule base.

The process of achieving local consensus would force local experts to codify and defend the assumptions and opinions that constitute the bulk of their tacit knowledge

base. Points of contention would clearly identify areas where local knowledge is inexact and would benefit from clarification. Points of general agreement would identify stable areas of widely accepted local knowledge. The process described here for allocating soils to relative landscape position is, in fact, quite generic and could be used to capture and apply many different kinds of tacit knowledge and could be modified to be applicable to any specified ecological region.

5.4.2 The concept of conditional and contextual allocation

The second unique aspect of the current procedures is that they are both relative and contextual. The facet, or facets, to which a soil is ultimately allocated depends upon the relative extent of the four landform facets in the landscape, on the particular combination and extent of soils presented to the program and on the relationships of the soils to each other as defined by their significant characteristics. The result is a procedure that is both general and remarkably powerful.

Imagine the difficulty of writing, maintaining and applying rules that referred to specific soils in specific combinations on specific landscapes. It would be virtually impossible to anticipate all possible combinations of soils and landscapes and to develop specific rules to state which soils occurred in which landform positions for each specific combination. For example, a specific rule base might state that soil A occurred in crest landform positions, except in cases where soil B was present, in which case soil A would occur in a mid-slope position. Image now that, for a given landscape, no crest positions were defined, where would soil A now be placed?

The use of estimates of relative likelihood for each soil for each landform position avoids this problem by enabling comparisons to be made for any combination of soils and landform, even unknown or unexpected combinations. One only has to know what soils occur in the landscape, the proportions in which they occur and the relative likelihood of each soil occurring in each landform position. For any combination of soils, one soil is almost certain to be more likely to occur in a given landform position that all of the others and will be allocated to that facet.

The procedure is flexible enough that if the known extent of the landform facet is greater than the reported extent of the most likely soil to occupy it, the remainder of the extent of the element is filled by allocating the next most likely soil to it, or the third most likely soil, if required, and so on. Similarly, if the reported extent of a listed soil is greater than the known extent of the landform element in which it is most likely to occur, that portion of the listed soil in excess of the extent of the landform element in which it is most likely to occur will be allocated to the landform element in which it is next most likely to occur.

Consider also the case of two soils that have identical likelihoods of occurring in a given landform position. The described method can accommodate such a situation by allocating equal proportions of each of the identical soils to the landform element in

question, thereby informing the user that both soils are equally likely to be found in that landscape position.

One question that arises from application of the example data is whether the procedure should accept as correct the estimates of the extent of each soil in each polygon or soil map unit. These estimates represent an average situation. At a specific site, the analyst's estimate of the extent of each soil (and therefore of each landform element) may differ significantly from the proportions of each landform element computed from quantitative analysis of a representative digital elevation model. In such cases, it might be preferable to adjust the proportions reported for each soil to reflect the extent of the landform elements it is most closely associated with. This is certainly an issue for potential future consideration. For the present, the proportions of each named soil estimated by the analyst are accepted and used.

6. PRODUCTION OF SOIL-LANDSCAPE MODEL DIAGRAMS

The final aspect of the current project was to produce 2D or 3D illustrations to assist in visualization of the pattern of distribution of soils for any given combination of soils and landscape.

6.1 Production of an annotated 3D illustration for the test site

The report generation facilities of a commercial data base management system program (***Fox Pro for Windows™***) were utilized to create a procedure for producing hard copy reports to illustrate the relationships between soils and landform.

The procedure made use of a 3D perspective diagram generated from a detailed DEM of the test site. The DEM was pre-processed to identify and delineate the 4 defined landform facets. The allocation procedures described in section 5 were implemented to automatically allocate all of the soils listed for the test site to each of the 4 landform elements. The allocation results, as well as a bit mapped image of the DEM classified into landform facets, were stored in appropriate fields of a provisional soil-landscape model database (see Appendix 4).

The program made use of the capability of the data base management system to store and print bit mapped images in combination with textual data. The bit mapped image was placed into a box in the centre of the page on a computer generated report form. The appropriate textual data pertaining to the soil codes and percent extent for each of the landform facets were extracted from the database and re-formatted to fill in four boxes, one for each landform facet. These label points were associated with each of the four landform facets by means of color coding and lines drawn from the boxes to the corresponding landform facets as depicted in the bit mapped image.

The result (Figure 33) depicts a 3D illustration of the landform type identified for the test site with four surrounding boxes, one for each of the four landform facets. Each box contains a listing of the soil code and percent extent for the soil or soils judged most likely to occupy the landform facet in question.

6.1.1 Production and storage of bit mapped 3D images

The procedures for computing landform facets were automated to the extent that computer programs were used to compute the terrain attributes required to classify each landscape into its component landform facets. A second computer program then classified each cell of a raster matrix into one of the four defined landform facets.

The 3D image used for demonstration purposes was created using the program RDRAPE from the public domain GIS package PC-Raster (van Deursen and Wesseling, 1992). Any program for draping a classified data set over a raster DEM that can produce a bit mapped image could be used instead of RDRAPE.

Soil Landscape Model
Computer Generated 3D Illustration

Soil-Landscape Model Code: EODY7/M1h

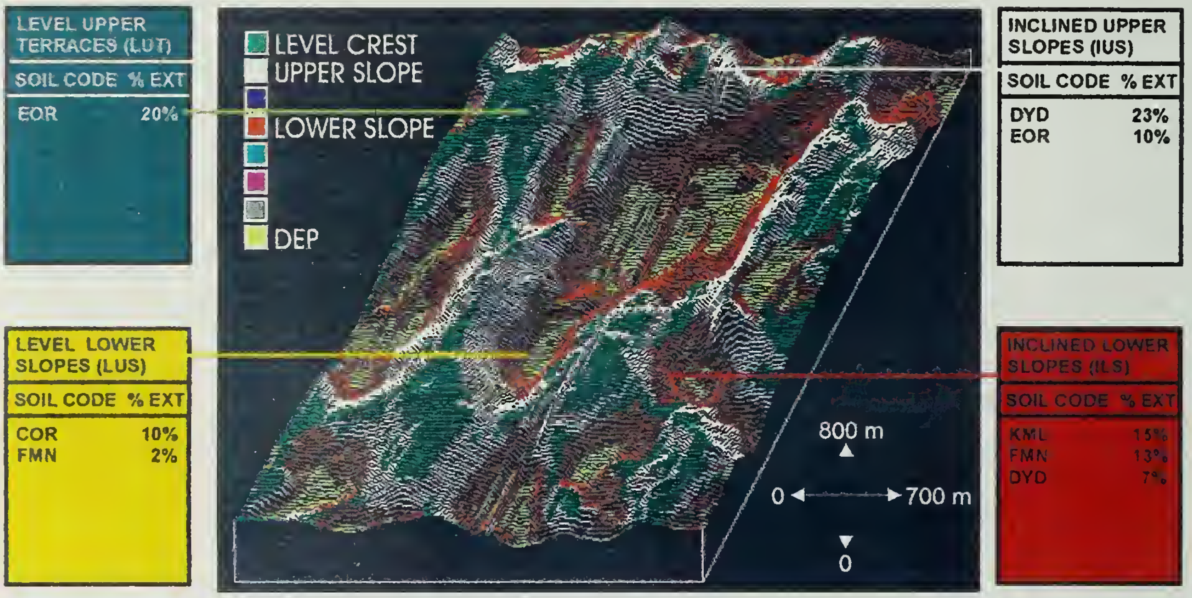


Figure 33. Example of a 3D illustration of a soil-landscape model for the test site

6.1.2 Design of a provisional soil-landscape model data base

A very simple data base was designed to store all of the information required to automatically label 3D illustrations with the code and percent extent of each soil present in each of the four defined landform facets (Table 12).

The example data base is highly non-normal in design, resulting in numerous cases of records with empty fields. For example, there will almost never be a case where the maximum allowed number of five soils occurs in all of the four defined landform facets. This non-normal design is highly inefficient in terms of data storage volumes and data redundancy but it does maintain a one to one relationship between soil-landscape model code (SLM_CODE) and listed soils.

The one to one relationship between soil-landscape model code (SLM_CODE) and listed soils greatly simplifies the process of generating a report in which soils are linked to one of the four defined landscape facets illustrated in a bit mapped 3D diagram. All that is required is a simple report form defined using the basic report generation facilities of a data base management system (***FoxPro for Windows***™ in this case). The report form prints the codes from the appropriate fields in the appropriate locations to produce a diagram that identifies the soils that occur in each landform facet and the proportions in which they occur. The soil-landscape model database (SLMD) (Table 12) is treated as a temporary file into which data for one or more soil map polygons of interest may be extracted.

6.2 Potential applications of annotated 3D illustrations

The procedure can be used to create an archive of soil-landscape model illustrations to assist users with visual interpretation and application of the soils data stored in existing and emerging digital soils data bases. Qualitative interpretation of digital soil map information would surely be enhanced by providing users with a graphical portrayal of the most likely relationship between soils and landform position. Quantitative applications of the digital data could also benefit if users were alerted to the pattern of distribution of soils within landscapes and used this information to devise and apply appropriate quantitative methods.

6.3 Evaluation of procedures for producing 3D illustrations

For reasons of simplicity, the general field (LM_3D) was included directly in the single FoxPro database used here to demonstrate the concept of automatic labeling of landform images. In any final, production, system it would be preferable to store the bit mapped images in a separate file containing a single 3D image for each defined landform type. This file would contain only two fields, a general field containing a 3D bit mapped image for each defined landform type and a field for landform model code (LM_CODE) to link each image to each landform type.

Table 12. Structure for simplified data base used to generate 3D illustrations

Field No	Field Name	Field Type	Width	Dec	Description
1	SLM_CODE	Character	13		Soil-Landscape Model Code
2	LM_CODE	Character	5		Landscape Model Code
3	SM_CODE	Character	7		Soil Model Code
4	F1_PCT	Character	3		Total percent extent of land facet No. 1 (LUT)
5	F1_S1	Character	7		Soil Code for dominant soil in land facet No. 1
6	F1_S1P	Character	3		Percent extent of dominant soil in land facet No. 1
7	F1_S2	Character	7		Soil Code for second soil in land facet No. 1
8	F1_S2P	Character	3		Percent extent of second soil in land facet No. 1
9	F1_S3	Character	7		Soil Code for third soil in land facet No. 1
10	F1_S3P	Character	3		Percent extent of third soil in land facet No. 1
11	F1_S4	Character	7		Soil Code for fourth soil in land facet No. 1
12	F1_S4P	Character	3		Percent extent of fourth soil in land facet No. 1
13	F1_S5	Character	7		Soil Code for fifth soil in land facet No. 1
14	F1_S5P	Character	3		Percent extent of fifth soil in land facet No. 1
15	F2_PCT	Character	3		Total percent extent of land facet No. 2 (IUS)
16	F2_S1	Character	7		Soil Code for dominant soil in land facet No. 2
17	F2_S1P	Character	3		Percent extent of dominant soil in land facet No. 2
18	F2_S2	Character	7		Soil Code for second soil in land facet No. 2
19	F2_S2P	Character	3		Percent extent of second soil in land facet No. 2
20	F2_S3	Character	7		Soil Code for third soil in land facet No. 2
21	F2_S3P	Character	3		Percent extent of third soil in land facet No. 2
22	F2_S4	Character	7		Soil Code for fourth soil in land facet No. 2
23	F2_S4P	Character	3		Percent extent of fourth soil in land facet No. 2
24	F2_S5	Character	7		Soil Code for fifth soil in land facet No. 2
25	F2_S5P	Character	3		Percent extent of fifth soil in land facet No. 2
26	F3_PCT	Character	3		Total percent extent of land facet No. 3 (ILS)
27	F3_S1	Character	7		Soil Code for dominant soil in land facet No. 3
28	F3_S1P	Character	3		Percent extent of dominant soil in land facet No. 3
29	F3_S2	Character	7		Soil Code for second soil in land facet No. 3
30	F3_S2P	Character	3		Percent extent of second soil in land facet No. 3
31	F3_S3	Character	7		Soil Code for third soil in land facet No 3
32	F3_S3P	Character	3		Percent extent of third soil in land facet No 3
33	F3_S4	Character	7		Soil Code for fourth soil in land facet No. 3
34	F3_S4P	Character	3		Percent extent of fourth soil in land facet No. 3
35	F3_S5	Character	7		Soil Code for fifth soil in land facet No. 3
36	F3_S5P	Character	3		Percent extent of fifth soil in land facet No. 3
37	F4_PCT	Character	3		Total percent extent of land facet No. 4 (LLS)
38	F4_S1	Character	7		Soil Code for dominant soil in land facet No. 4
39	F4_S1P	Character	3		Percent extent of dominant soil in land facet No. 4
40	F4_S2	Character	7		Soil Code for second soil in land facet No. 4
41	F4_S2P	Character	3		Percent extent of second soil in land facet No. 4
42	F4_S3	Character	7		Soil Code for third soil in land facet No. 4
43	F4_S3P	Character	3		Percent extent of third soil in land facet No 4
44	F4_S4	Character	7		Soil Code for fourth soil in land facet No. 4
45	F4_S4P	Character	3		Percent extent of fourth soil in land facet No. 4
46	F4_S5	Character	7		Soil Code for fifth soil in land facet No. 4
47	F4_S5P	Character	3		Percent extent of fifth soil in land facet No. 4
48	LM_3D	General	10		Bit mapped image of 3D illustration of land facets

7. SUMMARY AND CONCLUSIONS

1. This project represents a major advance by providing a landscape context for the application of soil survey information for modeling or land management uses.
    - landform attributes are quantified,
    - soils are linked to landform facets (a soil-landscape model is created),
    - the automated procedures use digital elevation data (DEMs) and standard soil survey information.
2. The data extracted from the automated morphometric analysis of DEMs provides a quantitative description of the landform.
    - ten attributes including slope gradient, length, aspect, curvature, relief and watershed characteristics are defined and characterized,
    - the analysis includes range, frequency distribution and spatial distribution of each attribute,
    - the information can be used alone or as input into a number of landscape dependent models,
    - the information becomes the basis for landscape segmentation and analysis.
3. A landform model based on both slope and relative relief is more realistic and robust than models based on the shape of individual pixel elements.
    - a basic eight unit model provides the flexibility to address different landforms and scales of information,
    - a simplified four unit model, formed by combining elements of the eight unit model, satisfies the need for practical, identifiable units for linking reconnaissance level soils information.
4. The allocation of soils to landform elements (the development of a soil-landscape model) can be automated using expert opinion that captures local tacit knowledge using a fuzzy logic or probability approach.
    - a rule base is developed based on the “relative likelihood” of soil attributes such as drainage and sub-group classification occurring in specified landform elements,
    - the approach requires no a priori knowledge of specific soil interactions or relationships,

- the approach is flexible and can be adapted to different ecological settings by generating a new rule base,
- the approach is generic and could be used to capture and apply other kinds of tacit knowledge

5. The production of 3D diagrams can be readily accomplished for any soil-landscape combination using commercially available database management (DBMS) software.
    - these automated diagrams can be generated from data used in development of the soil-landscape models,
    - the graphical product meets the requirement for a visual representation to facilitate the use and appropriate application of soil survey information..

8. RECOMMENDATIONS

1. Quantitative soil-landscape models should be a standard element of soil survey databases.

2. Assuming that there are a limited number of significantly different landforms, a DEM should be selected and quantitative landform analysis performed for an area deemed representative each type landscape.

   - a minimum of one area should be analyzed for each CAESA-SIP landform type
   - analysis of type landforms may be staged to quantify the most extensive landform types first

3. The segmentation procedure should be tested and procedures for combining and simplifying elements should evaluated for different types of landforms.

4. A "relative likelihood" rule base should be developed for each ecoregion in Alberta to support application of the soil allocation procedure.

   - the Alberta Soil Names File (SNF) should be modified to include new fields to record the "relative likelihood" that a soil occurs in each of the defined landform elements.

5. A standard electronic soil map unit form should be developed which includes basic soil and landform information as well as a representative soil-landscape model.

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APPENDIX 1: DESCRIPTION OF SOILS AT THE LUNTY SITE

Seven main soil series recognized and mapped at the Lunty site (Table 13) were described in terms of their relative landform position (MacMillan, 1994).

Table 13. Classification and characteristics of the 7 main soil series identified at the Lunty site

Soil Code	Soil Name	SubGroup	Drainage	Salinity	Variant	PM Type	PM Texture	Landform Position
EOR	Elnora	O.BL	W	NS	NA	TILL	MF	UPPER
HER	Heisler	SZ.BL	W	WS	NA	TILL	MF	UPPER
DYD	Daysland	BL.SO	W	WS	NA	TILL	MF	MID
KLM	Killam	BL.SS	MW	MS	NA	TILL	MF	MID
FMN	Foreman	SZ.HG	P	MS	FI	LACU	FI	LOWER
COR	Cordel	HU.LG	P	NS	FI	LACU	FI	TOE-DEP
HGT	Haight	O.HG	P	NS	FI	LACU	FI	DEP

Upper convex portions of the landscape consist of chernozemic (EOR) or weakly solonetzic (HER) soils. These upslope areas are characterized by rapid surface runoff, good internal drainage and maximum depth to water table. Soils in convex upslope positions are predominantly well to moderately well drained and either lack solonetzic features or display relatively weak solonetzic B horizons and weak accumulations of subsoil salts. Soils in non-permanently ponded depressions in upland landscape positions (COR) generally display features (Ae horizons) indicative of leaching and net downward movement of water into the soil.

Mid to lower slope positions are characterized by solonetzic soils (DYD & KLM). Increased accumulations of upslope runoff and lower slope gradients lead to a greater amount of infiltration than in upper slopes and produce an increased likelihood of saturation from above. Depth to water table is less than for upslope areas and there is a greater likelihood of saturation from below by moisture drawn up from the water table. Mid slope soils have moderately well to imperfect internal drainage.

Soils in lower landscape positions and depressions are poorly to very poorly drained and are classified as Gleysols. These are affected by the accumulation of surface runoff and by sub-surface groundwater flow. Gleysolic soils (HGT) at the centres of depressions characterized by nearly permanent ponding show strong gleying and no eluival horizons indicative of leaching. Soils in depressions that exhibit only short term ponding or soils near the outer edges of more permanently ponded depressions (COR) typically display features indicative of both leaching (Ae horizons) and periodic saturation from below (mottling). Soils in slightly elevated locations around the perimeters of the larger and more permanently ponded depressions are both strongly gleyed and strongly saline (FMN). They display both mottles and well developed solonetzic features including a solonetzic B horizon and visible accumulations of gypsum and soluble salts at shallow depths.

APPENDIX 2: A LANDSCAPE MODEL DATABASE

It has been previously recommended that landform morphological attributes be computed for one or more type locations selected as representative of each unique landscape type defined for the CAESA-SIP project and that the resulting quantitative data be stored in a landscape model database or databases.

The content and structure of the required landscape model database(s) have not yet been finalized, but an initial proposal envisages two separate databases. The first would contain highly detailed unclassed data enabling reproduction of the continuous frequency distributions of each variable for each type landscape (Table 13). The second would consist of a single record in the database for each type landscape (Tables 14-16). Each type landscape would be described in terms of the proportion of the landscape that fell into each of a limited number of defined classes for each attribute (e.g. defined slope classes as per ECSS, 1987b).

Table 14. Example of a database for detailed recording of morphological attributes for type landscapes

SITE NO	LANDSCAPE CODE	ATTRIBUTE CODE	MEAS UNIT	MEAS METHOD	CLASS NO.	LOW VAL	HIGH VAL	NO. OBS	% OF TOTAL	CUM %
1	M1h	SLP	PCT	EYTON	1	0	0.5	4300	26.8	26.8
1	M1h	SLP	PCT	EYTON	2	0.5	1.0	3700	23.1	50.0
1	M1h	SLP	PCT	EYTON	3	1.0	2.0	4200	26.3	76.2
1	M1h	SLP	PCT	EYTON	4	2.0	3.0	3800	23.8	100

The database for detailed recording of landscape attributes (Table 14) is designed to be flexible and to allow recording of as many discrete measurement intervals as are required to describe the continuous frequency distribution of any given variable. The number of discrete intervals will vary depending upon the morphological attribute of interest (i.e. slope gradient, plan curvature) but a practical limit might be about 100 intervals for any one variable. For example, slope gradient might best be recorded in equal class intervals of 1 percent, except for the first two classes which would have a class interval of 0.5 percent. Similarly, plan curvature might be recorded for unequal class intervals on a geometric scale (i.e. 0-1, 1-2, 2-5, 5-10, 10-20, 20-50, 50-100, 100-200, 200-500, 500-1000, 1000 plus degrees per 100 m).

The continuous frequency distribution data can be produced by any program that can count the number of occurrences of grid cells in a raster image within defined class intervals (i.e. the ***Histo*** module in ***Idrisi*** or the ***Describe*** command in ***PC-Raster***). It is suggested that each class of data be assigned a unique sequential number (CLASS NO. in Table 13) and that the data be entered into the database in this sequential order as illustrated. This will facilitate calculation of the cumulative frequency distribution.

Once the continuous frequency distribution data has been calculated and stored for a given morphological attribute for a given type landscape, it can be grouped or re-classed in any convenient fashion. It is expected that many users needs will be satisfied by classed data that summarizes the frequency distribution for commonly defined classes for each attribute (Tables 15-17). An advantage of this approach is that the major landform characteristics of each landscape type can be summarized in a single database record using defined classes that are familiar to most users. Many existing models and interpretive algorithms are designed to use such classed data. If the classes defined for the single record landform database (Tables 15-17) are not adequate, the distributions within new classes can be computed from the original detailed database.

The content and structure of the landscape model database documented in tables 15-17 is provided solely as an illustration of how a database to record frequency distributions for classes of morphological attributes for individual type landscapes might be set up.

Several of the attribute classes adopted for the example database are based on widely accepted classification systems (e.g. aspect, slope as per ECSS, 1983 and curvatures as per Young, 1972). Others such as slope lengths (LEN, LUP, LDN) and absolute relief (ABS) are entirely arbitrary. These classes would undoubtedly require appropriate review and modification by experts from the soils community prior to committing to a final database structure.

A finalized version of the landscape model database could be used as a look-up table to document the salient morphological characteristics of type landscapes. Type landscapes are presently identified for each polygon in the CAESA-SIP database by means of a standard landscape code. This landscape code can act as a pointer (see Figure 1) to the expanded, quantitative description of the principal morphological attributes of the landscape recorded in the proposed landscape database (Tables 15-17).

As indicated in Table 17, the database could include bit mapped (BMP) diagrams illustrating the spatial pattern of distribution of each of the measured morphological attributes.

The database could also include fields identifying the extent of each landscape occupied by each of ***n*** defined landform facets where ***n*** here equals 5 and the defined landform facets correspond to inclined upper slopes (IUS), level upper slopes (LUS), inclined lower slopes (ILS), level lower slopes (LLS) and depressions (DEP) as defined elsewhere in this bulletin.

A bit mapped diagram (FACET_BMP) could also be stored in the database to illustrate the spatial distribution of defined landform facets for each landscape. This image of a segmented landform is used to construct pictorial representations of soil-landscape models.

Table 15. Example landscape database

FIELD NAME	UNITS	LOWER VALUE	UPPER VALUE	EXAMPLE
LANDSCAPE MODEL ID	CODE	NA	NA	M1h
SLP_CLS1	PCT	0.0	0.5	
SLP_CLS2	PCT	0.5	2.0	
SLP_CLS3	PCT	2.0	5.0	
SLP_CLS4	PCT	5.0	9.0	
SLP_CLS5	PCT	9.0	15.0	
SLP_CLS6	PCT	15.0	30.0	
SLP_CLS7	PCT	30.0	45.0	
SLP_CLS8	PCT	45.0	70.0	
SLP_CLS9	PCT	70.0	100.0	
SLP_CLS10	PCT	100.0	PLUS	
LIM_SLP	CLASS#			
LIM_SLP%	PCT			
DOM1_SLP	CLASS#			
DOM1_SLP%	PCT			
DOM2_SLP	CLASS#			
DOM2_SLP%	PCT			
NO_ASPECT	DEG	NA	NA	
N	DEG	0	45	
NE	DEG	45	90	
E	DEG	90	135	
SE	DEG	135	180	
S	DEG	180	225	
SW	DEG	225	270	
W	DEG	270	315	
NW	DEG	315	360	
DOM_ASP	DEG			
ABS_CLS1	M	0	1	
ABS_CLS2	M	1	2	
ABS_CLS3	M	2	5	
ABS_CLS4	M	5	10	
ABS_CLS5	M	10	20	
ABS_CLS6	M	20	50	
ABS_CLS7	M	50	100	
ABS_CLS8	M	100	200	
ABS_CLS9	M	200	500	
ABS_CLS10	M	500	1000	
ABS_CLS11	M	1000	PLUS	
DOM_ABS	CLASS	NA	NA	
MEAN_ABS	M	NA	NA	

Table 16. Example landscape database (cont)

FIELD NAME	UNITS	LOWER VALUE	UPPER VALUE	EXAMPLE
LANDSCAPE MODEL ID	CODE	NA	NA	M1h
DCV_N5	DEG 100	-1000	-1000	
DCV_N4	DEG/100	-1000	-100	
DCV_N3	DEG 100	-100	-10	
DCV_N2	DEG 100	-10	-1	
DCV_N1	DEG 100	-1	0	
DCV_P1	DEG 100	0	1	
DCV_P2	DEG 100	1	10	
DCV_P3	DEG 100	10	100	
DCV_P4	DEG 100	100	1000	
DCV_P5	DEG 100	1000	PLUS	
DOM_DCV	CLASS	NA	NA	
MEAN_DCV	DEG 100	NA	NA	
XCV_N5	DEG/100	-1000	-1000	
XCV_N4	DEG 100	-1000	-100	
XCV_N3	DEG 100	-100	-10	
XCV_N2	DEG 100	-10	-1	
XCV_N1	DEG 100	-1	0	
XCV_P1	DEG 100	0	1	
XCV_P2	DEG 100	1	10	
XCV_P3	DEG 100	10	100	
XCV_P4	DEG 100	100	1000	
XCV_P5	DEG 100	1000	PLUS	
DOM_XCV	CLASS	NA	NA	
MEAN_XCV	DEG 100	NA	NA	
LEN_CLS1	M	0	10	
LEN_CLS2	M	10	20	
LEN_CLS3	M	20	50	
LEN_CLS4	M	50	100	
LEN_CLS5	M	100	200	
LEN_CLS6	M	200	500	
LEN_CLS7	M	500	1000	
LEN_CLS8	M	1000	PLUS	
DOM_LEN	CLASS	NA	NA	
MEAN_LEN	M	NA	NA	
LUP_CLS1	M	0	10	
LUP_CLS2	M	10	20	
LUP_CLS3	M	20	50	
LUP_CLS4	M	50	100	
LUP_CLS5	M	100	200	
LUP_CLS6	M	200	500	
LUP_CLS7	M	500	1000	
LUP_CLS8	M	1000	PLUS	

Table 17 Example landscape database (cont)

FIELD NAME	UNITS	LOWER VALUE	UPPER VALUE	EXAMPLE
LANDSCAPE MODEL ID	CODE	NA	NA	M1h
DOM_LUP	CLASS	NA	NA	
MEAN_LUP	M	NA	NA	
LDN_CLS1	M	0	10	
LDN_CLS2	M	10	20	
LDN_CLS3	M	20	50	
LDN_CLS4	M	50	100	
LDN_CLS5	M	100	200	
LDN_CLS6	M	200	500	
LDN_CLS7	M	500	1000	
LDN_CLS8	M	1000	PLUS	
DOM_LDN	CLASS	NA	NA	
MEAN_LDN	M	NA	NA	
PUP_CLS1	PCT	0	10	
PUP_CLS2	PCT	10	20	
PUP_CLS3	PCT	20	30	
PUP_CLS4	PCT	30	40	
PUP_CLS5	PCT	40	50	
PUP_CLS6	PCT	50	60	
PUP_CLS7	PCT	60	70	
PUP_CLS8	PCT	70	80	
PUP_CLS9	PCT	80	90	
PUP_CLS10	PCT	90	100	
DOM_PUP	CLASS	NA	NA	
MEAN_PUP	PCT	NA	NA	
NO_CATS	COUNT	NA	NA	
CAT_MEAN	HA	NA	NA	
CAT_DENS	NO HA	NA	NA	
OFF_SITE	PCT	0	100	
SLP_BMP	BMP	NA	NA	
ASP_BMP	BMP	NA	NA	
DCV_BMP	BMP	NA	NA	
XCV_BMP	BMP	NA	NA	
LEN_BMP	BMP	NA	NA	
LUP_BMP	BMP	NA	NA	
LDN_BMP	BMP	NA	NA	
PUP_BMP	BMP	NA	NA	
CAT_BMP	BMP	NA	NA	
IUS_PCT	PCT	NA	NA	
LUS_PCT	PCT	NA	NA	
ILS_PCT	PCT	NA	NA	
LLS_PCT	PCT	NA	NA	
DEP_PCT	PCT	NA	NA	
FACET_BMP	BMP	NA	NA	

APPENDIX 3: LANDFORM SEGMENTATION

Opportunities for improving the landform segmentation procedures

Several opportunities for improving the landform segmentation procedures might be considered. The first possibility for improving the classification would be to substitute use of a relative slope value as the break point for distinguishing low gradient from high gradient landform elements instead of using the currently proposed absolute value of 2% (class 2 slopes). Use of an absolute value for slope gradient will undoubtedly result in situations where most (or alternatively very few) of the grid cells in a given area have gradients less than the cutoff value. This situation was encountered in applying the criteria of Pennock et al. (1987) to the test DEM where almost all of the landscape was classified as planar because most grid cells had a slope gradient of less than 3 degrees.

It might be better to consider the frequency distribution of actual slope gradients in a given landform when distinguishing low from high gradient slopes in any landform. For example, in landforms characterized by steep slopes (15-40%) it might be advisable to define low gradient slopes as those less than 5% or 9% while in other, nearly planar, landforms characterized by very low slopes (0-2%) it might be necessary to select a value of 0.5% or 1.0% as the cutoff.

It may be necessary, for different landforms, to adjust the cutoff values of relative relief used to assign cells to upper, lower and depressional landform elements. One possible approach would be to determine the proportion of the landscape with shapes characteristic of shoulders, backslopes and footslopes according to the criteria of Pennock et al. (1987) and to select relative relief class limits that assign grid cells to each of the landform elements in approximately equivalent proportions. Another potentially useful modification would be to review the frequency distribution (histogram) of relative relief and identify the value of relative relief below which 50% of all grid cells fell. This value could then be used as the cutoff for differentiating upper slope elements from lower slope elements.

Possibilities for replacing the current procedure

It is felt that the classification might be improved by using fuzzy logic, in place of the current Boolean logic, to allocate each cell to its most appropriate landform element class. Fuzzy logic would provide a means of dealing with the uncertainty regarding the relative landform position of many grid elements. This uncertainty arises mainly from local scale effects that make it difficult to decide if the landform position of a given cell is best computed relative to a local divide or ridge or relative to the maximum elevation for each watershed.

Fuzzy logic would permit consideration of other factors, such as relative upslope length and relative downslope length, in assigning each cell to a landform element. For example, an upslope element could be defined as a grid cell which had a large value for local relative relief but also had a low value for upslope distance expressed as a percent and a high value for downslope distance expressed as a percent. In the language of fuzzy logic, an upslope cell would be described as “close” to a divide or ridge and “far” from a depression where “close” and “far” are both defined in relative terms. Similarly, a cell would be considered to be located in a lower slope position if it was relatively “close” to a depression and “far” from a divide, in addition to being “close” to the base elevation of the watershed in which it was contained. Midslope cells would be considered to be close to half way with respect to all of relative relief, relative downslope length and relative upslope length.

Utilization of fuzzy logic could provide a mechanism for merging considerations of relative landform position and surface shape. For example, the likelihood of a cell being classed as a shoulder element could be related to profile curvature in addition to relative relief with greater likelihood associated with greater convexity. Similarly a concave grid cell would have a higher likelihood of being classified as a foot-slope element and a planar grid cell would be more likely to be classed as a back-slope.

It was originally intended to implement and evaluate a landform element classification based on fuzzy logic. Ultimately, this did not prove possible due to time restrictions. Additionally, the four unit model based on application of Boolean rules to relative relief and slope gradient data was deemed to be adequate for the required application. The potential improvement in accuracy and robustness of classification did not warrant the extra effort required to develop, apply and evaluate an approach based on fuzzy logic. This remains an interesting area for future work.

APPENDIX 4: GENERATION OF 3D DIAGRAMS FOR THE CAESA-SIP DIGITAL DATABASE

Population of a SLMD data base from CAESA-SIP data

The process of populating the temporary soil landscape model database (SLMD file) involved extracting data from several other data bases, some of which currently exist and are in use by the CAESA-SIP project and others which must be generated by methods described previously.

The landscape model code (LM_CODE) was read directly from the CAESA-SIP soil landscape attribute (SLA) file for each polygon of interest. The code was then used to look up the required data for each landform in a landscape model data base (LMD). The LMD data base does not currently exist as part of the CAESA-SIP data structure, but has been proposed and described previously (see section 7.2). The data from the proposed LMD required for the present application included the percent of the landscape classified into each of the four simple landform facets (F1_PCT, F2_PCT, F3_PCT, F4_PCT) and a pointer to a picture file that contained a previously prepared bit mapped image of the landscape classified into its 4 component landform facets.

The CAESA-SIP master soils (MAS) file contains a listing of the soil codes for up to 5 soils in each polygon. The proportional extent of each soil in each polygon was reported in the CAESA-SIP MAS file using codes for dominant, co-dominant, significant or inclusion. These codes were not directly useable as numeric percents. A previously developed procedure was used to produce reasonable numerical estimates for each code based on consideration of the specific combination of proportion codes listed for any given polygon. The soil codes (including modifier code) for each soil listed in the CAESA-SIP MAS file were extracted from the MAS file along with the codes for proportion of each soil. These were then processed using the previously developed routines to convert proportion codes into estimates of numerical percent.

It has been previously recommended (MacMillan, 1996d) that a value for relative likelihood of occurring in each of the 4 previously defined landform facets be computed and stored as an attribute of every soil in an extended Alberta soil names file (SNF). If this has been done, then the soil plus modifier codes extracted from the CAESA-SIP MAS file can be used to look up, in the extended SNF, the relative likelihood of each listed soil occurring in each landscape position. Otherwise, as was the current case, the procedures for computing relative likelihood values for each soil need to be run and the results stored in a separate file.

The previously described allocation procedures (MacMillan, 1996d) were then run to automatically allocate all of the soils listed for the selected soil-landscape combination to each of the 4 defined landform elements. The automated allocation procedures required the following data:

1. estimates of the proportional extent of each of the 4 landform facets for the current landform (extracted from a LMD file as described above and stored into the fields F1_PCT, F2_PCT, F3_PCT, F4_PCT respectively).
2. estimates of the proportional extent of each of the soils listed as occurring in the current polygon (extracted from the MAS file and processed to convert proportion codes to percent estimates as described above)
3. calculated values of the relative likelihood of each of the listed soils occurring in each of the 4 defined landform facets (extracted from the SNF or computed as described above)

The program to allocate soils to landform elements was run and the resulting allocations stored into the appropriate fields of the SLMD data base (Table 18).

In the case of the example data, level upper terraces (Facet 1) constituted 20% of the landscape and the single soil series (EOR) judged most likely to occupy that facet was estimated to comprise 30% of the total landscape. Thus, facet 1 (LUT) was computed to be completely occupied by EOR soils (20%). The code EOR was stored in the field F1_S1 (Facet 1-Soil 1) and the value 20 stored in the field F1_S1P (Facet 1 - Soil 1 Percent). All of the other fields pertaining to facet 1 (i.e. F1_S2, F1_S2P, etc.) remained empty. Facet 4 (LLS) was then considered and determined to constitute 12% of the total landscape. The soil deemed most likely to occur in a level lower slope or depression (LLS) was COR which was estimated to occupy 10% of the landscape.. The code COR was stored in the field F4_S1 (Facet 4-Soil 1) and the value 10 stored in the field F4_S1P (Facet 4 - Soil 1 Percent). This left 2% of facet 4 (LLS) unallocated so 2% of the soil deemed next most likely to occupy this facet (FMN) was identified. The appropriate soil code (FMN) was stored into the field F4_S2 (Facet 4-Soil 2) and the appropriate percent extent (2) was stored into the field F4_S2P). The process was completed by processing facets 2 (IUS) and 3 (ILS) in a similar manner and storing the soil codes and percent extents to the appropriate fields.

The completed data base (Table 18) contained all of the data required to produce a hard copy report illustrating the distribution of soils by landform facet.

Table 18. Illustration of the example data entered into the soil-landscape model data base

Field No	Field Name	Value Stored for Single Example Data Set
1	SLM_CODE	EODY7/M1h
2	LM_CODE	M1h
3	SM_CODE	EODY7
4	F1_PCT	20
5	F1_S1	EOR
6	F1_S1P	20
7	F1_S2	
8	F1_S2P	
9	F1_S3	
10	F1_S3P	
11	F1_S4	
12	F1_S4P	
13	F1_S5	
14	F1_S5P	
15	F2_PCT	33
16	F2_S1	DYD
17	F2_S1P	23
18	F2_S2	EOR
19	F2_S2P	10
20	F2_S3	
21	F2_S3P	
22	F2_S4	
23	F2_S4P	
24	F2_S5	
25	F2_S5P	
26	F3_PCT	35
27	F3_S1	KLM
28	F3_S1P	15
29	F3_S2	FMN
30	F3_S2P	13
31	F3_S3	DYD
32	F3_S3P	7
33	F3_S4	
34	F3_S4P	
35	F3_S5	
36	F3_S5P	
37	F4_PCT	12
38	F4_S1	COR
39	F4_S1P	10
40	F4_S2	FMN
41	F4_S2P	2
42	F4_S3	
43	F4_S3P	
44	F4_S4	
45	F4_S4P	
46	F4_S5	
47	F4_S5P	
48	LM_3D	Gen